



## European Research in Marine Structures

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# European Research in Marine Structures

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## Abstract

An overview is presented of the results obtained in Europe by a network with a large number of research groups in the field of Marine Structures during a period of 6 years. The European Union has funded a project aimed at improving the collaboration among European research groups specialized in marine structures, which has led, among other results to a number of benchmark studies organized in 6 main topical areas, namely, Methods and Tools for Loads and Load Effects, Methods and Tools for Strength Assessment, Experimental Analysis of Structures, Materials and Fabrication of Structures, Methods and Tools for Structural Design and Optimization and Structural Reliability, Safety and Environmental Protection. This paper presents an overview of various studies performed, which helps identifying the level of consistency and robustness of different numeric tools used in this field.

## 1. Introduction

The European Union has funded MARSTRUCT, the Network of Excellence in Marine Structures, in which has 33 research groups from Universities, Research Institutions, Classification Societies and Shipyards have cooperated during 6 years aiming to increase their strength and complementarity. The background was the recognition that each of the existing research groups has some areas of expertise but in general lacks critical mass to deal with the wide variety of problems required to analyze and design marine structures. The network aimed at facilitating cooperation and building the critical mass through inter institution cooperation. This objective was to be achieved through a program for jointly executed research in the area of structural analysis of ships, the sharing of research facilities and platforms and a continuous program of dissemination and communication of research results. The way in which the program was designed contributed to the mutual specialization and complementarity through building up of strengths and the shrinking of weaknesses of the participants.

Although the funding was not negligible, it was aiming at promoting cooperation and thus each institution could only perform limited amounts of basic research. This was an incentive to completing tasks from previously concluded projects or doing joint work with others

groups, often intercomparisons of calculation tools or sharing of experimental results or infrastructures.

The activities of the Network cover different areas related with advanced structural analysis such as:

- Methods and Tools for Loads and Load Effects assessment for the various modes of structural response.
- Methods and tools for the analysis of the structural strength and performance, including aspects such as ultimate strength, fatigue, crashworthiness, fire and explosion, blast resistance, and noise and vibration.
- Experimental analysis of structures
- Influence of fabrication methods and new and advanced materials on the structural strength and performance of ships.
- Tools for design and optimization of ship structures.
- Tools and methods of structural reliability, safety and environmental protection of ships, which are organized in the various workpackages of the project.

The project has produced many research results that contributed to advance the state of the art in the various areas relevant to ship structures, which make more than 400 journal and conference papers 3 journal special issues (Guedes Soares and Das, 2008a,b Guedes Soares, 2011), and 3 books with the proceedings of international conferences(Guedes Soares and Das, 2007, 2009, Guedes Soares and Fricke, 2011). Of particular interest are several benchmark studies produced, namely:

- Comparison of experimental and numerical loads on an impacting bow section
- Comparison of experimental and numerical impact loads on ship-like sections
- Evaluation of slamming loads on V-shape ship sections with different numerical methods
- Comparison of experimental and numerical sloshing loads in partially filled tanks
- Simulation of the behavior of double bottoms subjected to grounding actions
- Round robin study on structural hot-spot and effective notch stress analysis
- Effect of the shape of localized imperfections on the collapse strength of plates
- Parametric study on the collapse strength of rectangular plates with localized imperfections under in-plane compression
- Benchmark study on the use of simplified structural codes to predict the ultimate strength of a damaged ship hull
- Studies of the buckling of composite plates in compression
- Fabrication, testing and analysis of steel/composite DLS adhesive Joints
- Simulation and optimization of the ship production process;
- Benchmark on ship structural optimization
- A benchmark study on response surface method in structural reliability
- Modeling strength degradation phenomena and inspections used for reliability assessment based on maintenance planning
- Current practices and recent advances in condition assessment of aged ships

The results of some of the benchmark studies will be summarized here as well as the results of some other specific studies and experimental programs. It is hoped that this may provide a comprehensive view of part of the work done and bring attention to some of the results considered to have applicability in the industry. The paper is organized in the various subject areas indicated above.

## 2. Methods and Tools for Loads and Load Effects

The calculation tools and knowledge that will allow the prediction of hydrodynamic loads are essential for design. The main ones focused on both the operational as well as accidental loads on ships, with limited attention to the description of the environment that the marine structures are subjected to. Some attention was devoted to the databases which are the basis to define the design wave climate and also on aspects of prediction of extreme waves and occurrence of abnormal or freak waves.

A limited effort was made in the benchmarking of codes for linear wave induced loads and the main emphasis was concentrated on wave induced loads in flexible ships. Special phenomena like slamming, green water and sloshing was considered and benchmark studies have been made on these topics. This chapter will include a brief description of one such study that had not yet been reported.

Accidental loads due to fires, explosions, collisions and grounding are equally important as design parameters for ships although difficult to predict. Through passive safety measures in the structural design, the safety of ships and the environment can be improved when adequate accidental load models are available. The load modeling includes also the behavior of the damaged ship in waves, an important aspect in the reliability assessment of collision and grounding scenario.

This chapter will also include an overview of the work done concerning the prediction of the grounding loads as well as the loads due to abnormal or freak waves, which due to their rare nature are also considered as accidental situations.

### 2.1 Comparison of numerical and experimental slamming impact pressures

Accurate prediction of slamming forces is important to enable their incorporation within methods that evaluate wave-induced motions so that transient induced wave loads can be estimated. Various methods and tools are available and thus a benchmark study was undertaken on the numerical evaluation of pressures and forces acting on impacting two-dimensional sections, comparing with available experimental data obtained from drop tests, with the aim of assessing the quality of predictions obtained from a range of numerical methods.

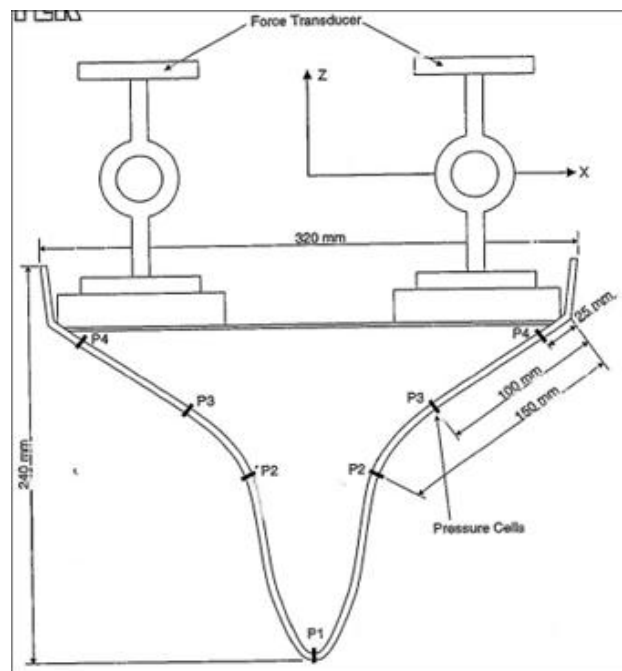
The bow section attached to a free falling rig, shown in Figure 1, was selected as one of the subjects of investigation due to its ship-like shape and the range of experimental conditions tested. Numerical investigations focused on tests with low ( $\approx 0.6\text{m/s}$ ) and high ( $\approx 2.4\text{m/s}$ ) drop velocities, with the variable velocity profile available from the measurements, and 3 angles of heel, namely  $0^\circ$ ,  $9.8^\circ$  and  $28.3^\circ$ . The points where pressures were measured using pressure cells, namely P1, P2, P3 and P4, are shown in Figure 1. In addition to pressures, measurements of vertical and, for rolled section impact, horizontal forces were recorded. To ensure 2D flow the total drop section was divided into three parts, namely one measuring section with a dummy section on each side. Further details of the experimentation and measurements are presented by Aarsnes (1996).

A list of the methods used for the modeling of the bow section impact is shown in

Table 1, which also includes details of the idealization and modeling of the impact velocity profile. In selecting the methods, both potential and non-potential (or RANS) flow concepts were included.

The Boundary Element Methods (BEM) fall in the potential flow category. They are all based on the same formulation, described by Zhao et al (1996) as the simplified rather than the fully nonlinear approach, which is a zero gravity potential theory formulation similar to the Wagner method but with boundary conditions satisfied on the real body surface. It accounts for water pile-up, but does not model jet flow. Only the methods denoted as BEM1 and BEM3 account

for flow separation from the knuckle. Furthermore each method has used different body and free surface idealizations, as can be seen in Table 1.



**Figure 1- Bow section and test rig (Aarsnes 1996)**

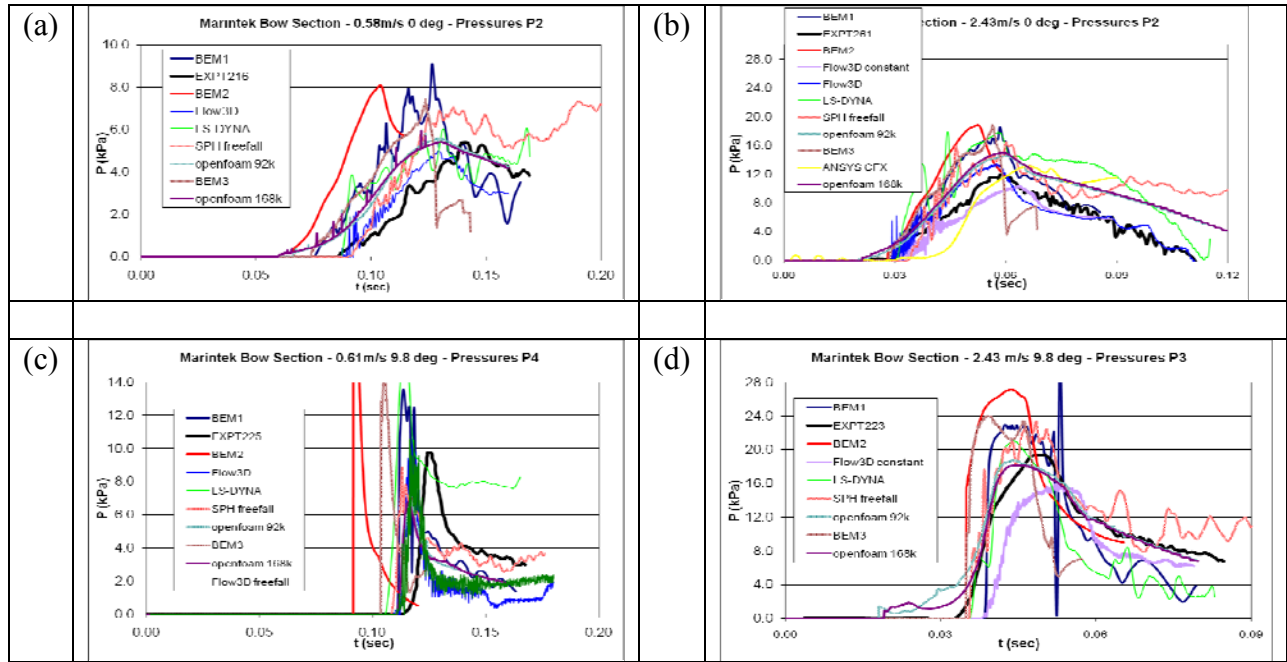
**Table 1- Details of methodology and idealization**

Method	Idealization and Impact velocity profile
BEM1 (1)	SB= 160, FS=240 (*); imposed velocity profile
BEM2 (2)	SB=301, FS=300 (*); linear approximation to experimental velocity profile
BEM3 (3)	SB=90, FS=50 (*); imposed velocity from experiment
ANSYS CFX (4)	30000 cells; free fall

Method	Idealization and Impact velocity profile
FLOW3D (5)	500 x 375 grid + refinements; (a) imposed velocity from experiment (b) constant (c) free fall
LS-DYNA (6)	31250 fluid (8-noded); 180 solid shell elements; imposed velocity from experiment
OpenFOAM (7)	42370, 91642 (92k) & 168066 (168k) nodes; velocity imposed from experiment, but smoothed
SPH (5)	250000 particles (diam. 1.75mm); (a) imposed velocity from expt. (b) constant (c) free fall

(\*) Segments on SB : Submerged Body, FS : Free Surface  
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- (3) Det Norske Veritas, Norway,
- (4) University of Southampton, UK,
- (5) DINAV, University of Genoa, Italy,
- (6) Principia, France,
- (7) Bureau Veritas, France.



**Figure 2- Example of pressure predictions and comparison with experimental measurements, for the bow section shown in Figure 1, at (a) P2, 0.58m/s, 0°, (b) P2, 2.43m/s, 0°, (c) P4, 0.61m/s, 9.8° and (d) P3, 2.43m/s, 9.8°.**

The commercially available software ANSYS-CFX, FLOW3D, LS-DYNA and the open source openFOAM fall within the RANS category. A range of mesh densities are used to model the air and fluid domains, as can be seen in

Table 1. It should be noted that LS-DYNA allows for the modeling of both the fluid and body domains, thus can be used for hydroelastic slamming. The final method in the RANS category is the Smoothed Particle Hydrodynamics (SPH) approach developed by Viviani et al (2009).

Numerical predictions of pressures at all four positions and slamming forces were obtained for all the aforementioned test conditions. A selection of pressures is shown in Figure 2. Pressures and forces predicted by the various numerical methods show differences between each other and the differences become greater with increasing impact speed and heel angle. Different assumptions were used for the impact velocity profile, as can be seen from Table 1. Simulating the velocity profile measured in the experiments, following impact is of vital importance in obtaining accurate pressure estimates at low impact speeds. During the investigations it was noted that use of the actual velocity profile resulted, in general, in oscillations in some RANS based solutions, e.g. FLOW3D and, especially in SPH.

The free fall concept, whereby the impact velocity is assigned as initial velocity as the section is about to impact, appears to work well in terms of eliminating such oscillations, especially for SPH; hence, only results for SPH with freefall are provided.

The use of constant speed at higher impact speeds is also suitable. Example of such influences can be seen in the pressures of Figure 2(b), constant vs velocity profile for higher impact speed (compare Flow3D constant vs Flow3D), and Figure 2(c), free fall vs velocity profile for lower impact speed (compare Flow3D freefall vs Flow3D).

All BEM methods show relatively sharp peaks in pressures. They all overestimate by comparison to the experiments. The influence of the velocity profile is evident in the early peak seen from BEM2, for the lower impact speed. BEM1 shows more oscillations compared to BEM3, probably due to the different mesh used for body and free surface idealization. Limited studies on mesh refinement carried out with openFOAM indicate good convergence, in general, for the meshes with 91,642 (92k) and 168,066 (168k) nodes respectively, as can be

seen in Figure 2. Overall RANS based methods produce the closest agreement with experimental measurements. In particular, openFOAM appears to provide consistent predictions of good quality, Flow3D and SPH also compare well in spite of some oscillations still being present. There isn't enough data for CFX to make an overall judgment and LS-DYNA can result in some good predictions but not consistently.

The importance of the investigations carried out is the systematic approach followed in assessing the predictions of potential and RANS methods, looking at the influence of impact speed, angle of heel, position along the section contour and mesh sensitivity. The results indicate that there is a need for further investigations, such as the use of the fully nonlinear approach for BEM, use of more refined meshes for some RANS methods, e.g. LS-DYNA, and application to the impact of other sections with available experimental measurements.

More details about the methods and models used as well as more results have been reported by Brizzolara et al (2008) and Temarel (2009).

## ***2.2 Simulation of the behavior of double bottoms under grounding actions***

Grounding as well as collision simulations involve high geometric and material nonlinearities, friction between structural components that slide on one another, material failure and buckling modes of failure of structural components. Taking these aspects into consideration it is obvious that finite element codes offer obvious advantages: the modeling allows the description of complicated geometries, the material modeling is far more realistic rather than the material models that are incorporated in analytical techniques, and it is not necessary to assume a priori the failure modes of the structural components as it is needed when using upper and lower bound theorems for the prediction of collapse strength of structures.

However, despite the availability of a number of appropriate FE codes, such as LS-DYNA, ABAQUS, DYTRAN, there are not widely acceptable guidelines for a FE simulation and in particular for the discrimination of the structure and the definition of the material model. Therefore the use of finite element codes is linked with uncertainties that need special consideration: typical results, such as force vs. penetration curves, strain and stress patterns, even failure modes, depend on the selection of mesh and element type, on the material deformation and failure models.

With respect to the simulation of the behavior of the material there are still uncertainties, in particular related to the failure criteria under multiaxial stress states and the representation of hardening in the plastic range under varying strain rates. Accordingly, it is highly desirable to compare the predictions of independent FE simulations of grounding incidents, in order to quantify the impact of the uncertainties related to the modeling technique and the solvers on the simulations' results. The study conducted aimed at analyzing and quantifying the differences that may arise

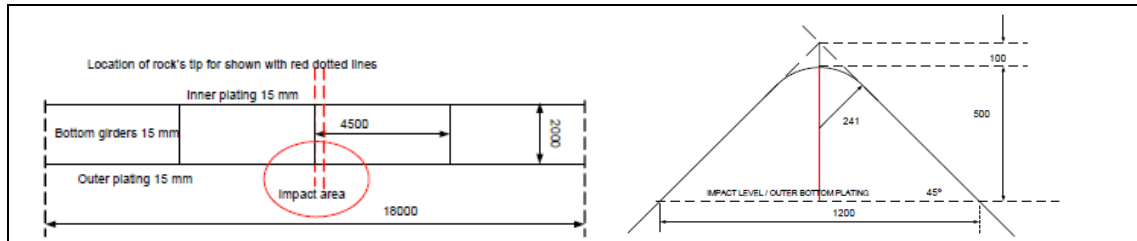
- i. as a results of the selection of independent parameters, in particular mesh size, relative speed between ship and sea-bed; and
- ii. when two independent teams simulate the same grounding.

### ***2.2.1 Selection of independent parameters for FE simulations***

Samuelides et al (2007b) reported on an extensive series of simulations of grounding of a double bottom on a rock, aiming at identifying guidelines that may be used to obtain numerically stable results when simulating grounding incidents with the explicit FE code ABAQUS. The model of the double bottom that was used is shown in Figure 3a and the rigid obstacle that comes in contact with the double bottom is presented in Figure 3b. The

investigation was based on simulations employing three different models of the double bottom:

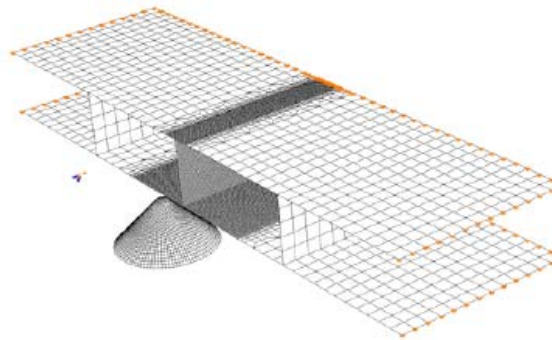
- ✓ a coarse mesh with shell elements having a length of 100 mm,
- ✓ a medium mesh with elements of 50 mm length (see Figure 4), and
- ✓ a fine mesh with shell elements having a length of 25 mm.



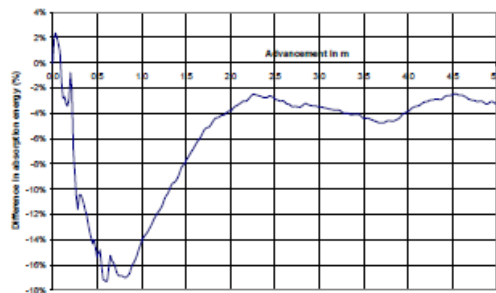
**Figure 3a(left) - Model of double bottom**

**Figure 3b (right) - Model of rock-conical obstacle**

Preliminary runs revealed that the indenter speed was found to have a small effect on the computed structural response and the calculated resisting forces and it was concluded to use an indenter speed equal to 10 m/s. The elements used for the modeling were reduced integration 4 node shells with 5 through thickness (Simpson) integration points. Figure 5 shows that there is a substantial underestimation of the energy at the initial stages of the contact when using 5 layers instead of 7, but the differences reduce to around 4% in the span where the force response exhibits a steady state, as it happens when the obstacle is moving in the area between the floors. The relative vertical position of the apex of the rock with respect to the outer shell was selected to be 0.5 m. In the transverse direction the indenter was either aligned with a girder or at a distance of 300 mm away from it.



**Figure 4- Model of the double bottom with no girders and the conical rock**



**Figure 5- Differences in energy predictions when using 5 vs. 7 through thickness integration points**



The investigation illustrated how the element size affects the mode of response of the girder. When the element size is 100mm the folds of the girder are not as apparent as in the models with the fine and medium meshes (Figure 6). However, in the absence of rupture, the medium and fine meshes produce similar deformation modes and the out-of-plane displacement in the medium and fine models also exhibit similar distributions. Further, the results obtained with the 25 mm and 50 mm meshes exhibit a relatively steady state force when the obstacle is approximately along a distance that extends from a point located 29% from the initial contact until 32% from the end boundary of the model. The mesh refinement studies suggest that a 50mm x 50mm shell elements, with five through thickness integration points, is sufficient for the accurate prediction of the forces. Trial runs indicated that the use of a 25mm square element size in the modeling of a longer structure including four or more floors, currently leads to impractical computational times.

Further simulations were performed considering a material failure criterion based on a maximum strain depending on the size of the element. These runs provided consistent results, particularly concerning the sensitivity of element size on the rupture strain value (50mm square element, 22% rupture strain and 100mm square element, 13.7% rupture strain). The reduction in the longitudinal force magnitude was found to be significant, less than half when the “element failure” was neglected. Figure 7 shows the deformation and failure modes in the plate and girder from the analyses with the 100 and 50mm models. However, despite the reasonably good agreement in the predicted longitudinal force curves, there are differences in the failure modes of the two models. It can be argued that this is the consequence of the ‘damage’ zone being localized along the girder-plate intersection with plastic strain magnitudes well in excess of those required to induce rupture.

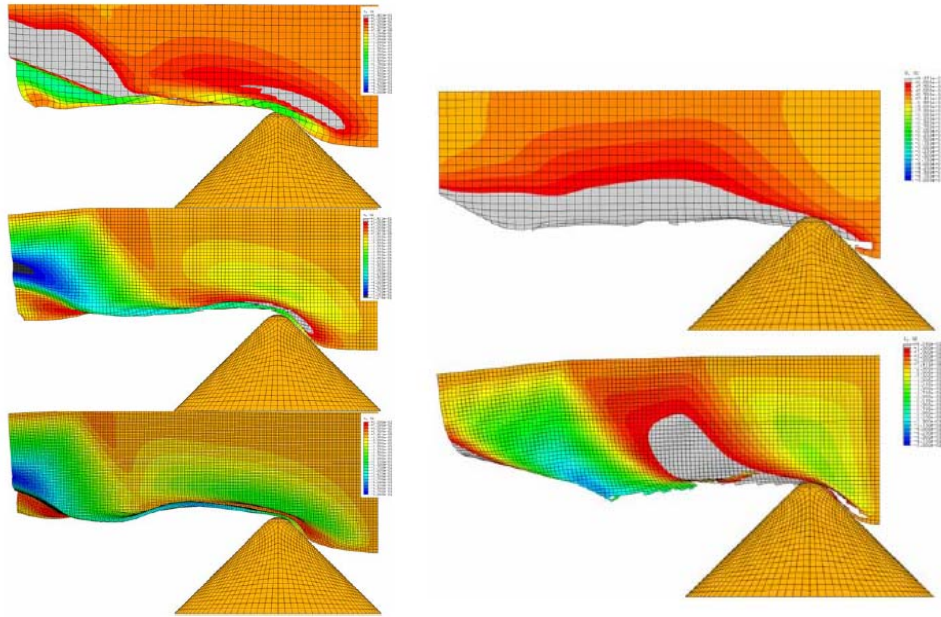
### *2.2.2 Benchmark study*

For the benchmark study the partners used the FE codes ABAQUS and LS-DYNA were used to simulate a section of the double bottom structure of a tanker subjected to a grounding action. The vessel considered is a 265 m long tanker with a displacement of 150000 tons and her double bottom geometry is shown in Figure 8. Details of the structure may be found in (Zilakos et al. 2009).

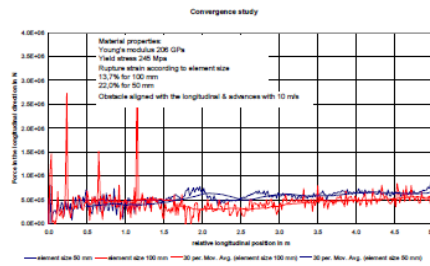
A three bay section of the double bottom, with a length of 15 m and spanning the entire breadth at the middle section of the vessel has been modeled. Three separate models have been constructed in order to examine the effect of the longitudinal stiffening on the grounding action: (a) a model including the girders but excluding all longitudinal stiffeners; (b) a model with longitudinal stiffeners attached to the inner and outer bottom plating; and (c) a model including all stiffeners, i.e. including the flat bar stiffeners in the plating and girders.

The grounding actions have been imposed on the double bottom through the motion of a conical shaped rigid indenter in the longitudinal direction of the ship. Two scenarios of grounding have been studied: impact on a longitudinal girder and also on the plating between two girders. Following previous studies (Samuelides et al, 2007b) the size of the elements were selected 50 mm in the contact area and 200 mm elsewhere.

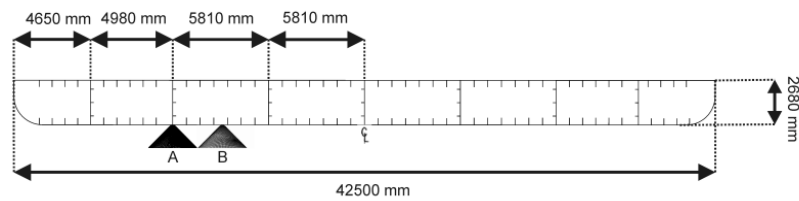
Prior to examining the predictions from the two codes, it was pertinent to examine the effect of the longitudinal stiffening on the plating and girders for contact aligned with a longitudinal girder or off-girder. Accordingly, the longitudinal and vertical reaction forces are shown in Figure 10, illustrating a gradual increase of the longitudinal force as stiffening is added to the model. Figure 10 shows however that there is only a small increase in the vertical force when comparing the fully stiffened and only on plating stiffened models. As in the case of impact on the girder, it can be seen that the inclusion of the stiffeners leads to significantly higher reaction forces.



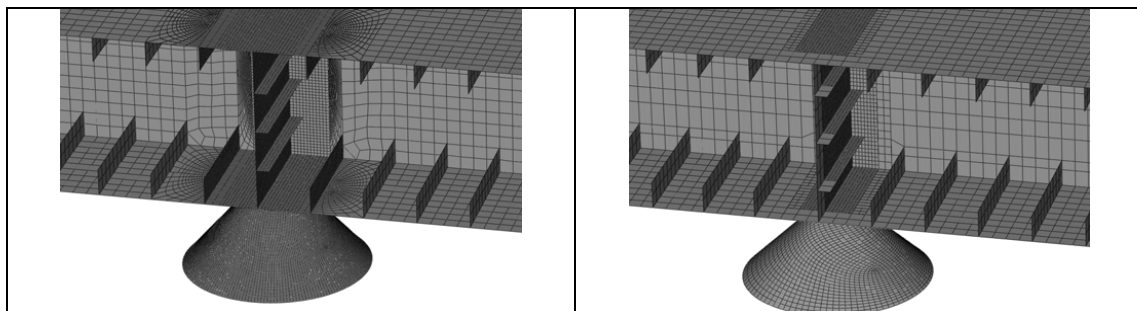
**Figure 6- Effect of mesh size on the deformation modes of the girders and out-of plane displacement; with no rupture from top to bottom mesh size is 100 mm, 50 mm and 25 mm (left); with rupture from top to bottom mesh size is 100 mm & 50 mm (right)**



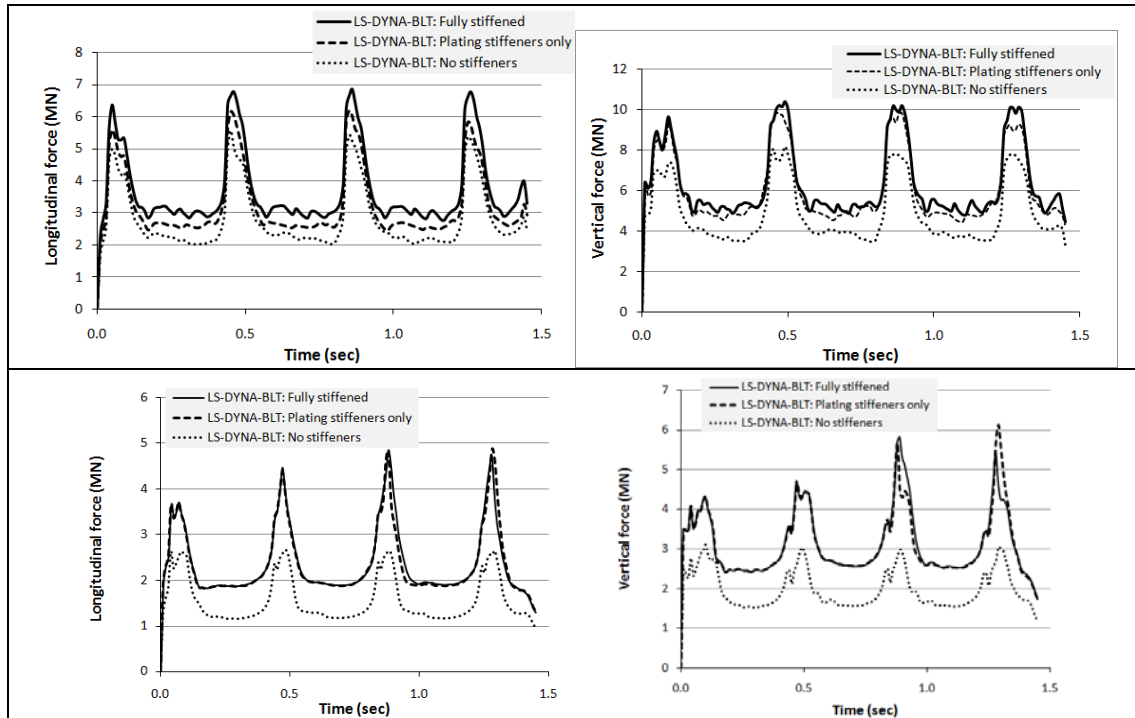
**Figure 7- Longitudinal reaction force vs. advancement: effect of mesh size including material failure**



**Figure 8- Geometry of double bottom**

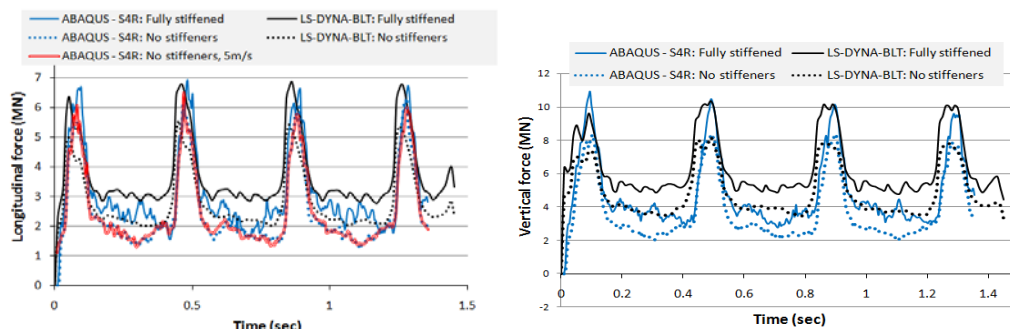


**Figure 9- Mesh design in the vicinity of the impact zone for the impact on girder: (left) LS-DYNA model, (right) ABAQUS explicit model.**



**Figure 10- Reaction force versus advancement (speed 10 m/s) illustrating the effect of stiffening elements. Top: Impact on girder, bottom: impact off girder, left: longitudinal force, right vertical force.**

However, when comparing the fully stiffened and plating only stiffened models, it is evident that the reaction forces are very similar. This is attributed to the ‘localized’ deformation induced by the impactor without spreading to the neighboring girders which remain almost intact. Clearly this result will change if a wider impactor was used in the simulations or if the penetration depth was larger. In the present work the width of the conical impactor that contacts the outer plating is approximately 1200mm while the distance between the two adjoining girders is 5810mm, (see Figure 8).



**Figure 11- Comparison of independent simulations: left: longitudinal reaction force, right: vertical reaction force**

A key prerequisite for the wider application of the Finite Element Method in the design of ships against grounding and other collision accidents is the reliability of the predictions. In this context, a series of grounding simulations of the double bottom structure were performed independently using the FE codes ABAQUS explicit and LS-DYNA. In order to reduce the uncertainty of the comparison, the same mesh topology and element sizes were used overall, although certain differences in the topology remained in the transition from the fine to coarse mesh regions due to different features in the two codes. In both cases the models were formed with one point quadrature shell elements with 5 through thickness integration points. However

the element formulations differed, using in LS-DYNA a popular shell element developed by Belytschko and co-workers while selecting in ABAQUS a finite (logarithmic) membrane strain alternative. The simulations considered two possible scenarios for grounding that is impact on a longitudinal girder and on the plating, in-between girders. Results in terms of longitudinal and vertical reaction forces are presented in Figure 11.

The reaction forces computed with the two FE codes for the spaces between two transverse floors were found to differ in the range of 15-30%. There was, however, closer agreement in the force peaks obtained as the impactor crosses each floor present in the model.

### **2.3 Load Effects Induced by Abnormal Waves**

Current design methodologies do not consider explicitly the wave conditions associated with the encounter of ships with abnormal or freak waves. This is because the probabilistic models describing the waves do not include the abnormal waves that modify the upper tail of those distributions.

Some of the mechanisms that can generate abnormal waves have been identified and reviews of the literature about them can be found in Kharif, and Pelinovsky (2003) and in Guedes Soares et al. (2003) for example. The definition of which waves should be considered as abnormal ones is also not commonly agreed as discussed in those references, but a criterion adopted by some authors is the ratio of the abnormal wave height by the significant wave height being larger than 2.0.

Although current design methods do not consider explicitly the abnormal wave conditions, Faulkner and Buckley (1997) suggested that the methods to determine the design loads should be revised to account for the effects of the abnormal waves on the ship structure.

In order to consider the structural loads induced by these conditions, a method was proposed by Fonseca and Guedes Soares (2001) to calculate the structural loads induced by deterministic wave traces of abnormal waves, where the ship responses are calculated by a nonlinear time domain seakeeping code. Using this approach the authors carried out several studies related to the responses of a floating platform induced by abnormal waves that were actually measured at the sea. A summary of these studies is presented here, which include also, for comparative purposes, the analysis of the responses induced by design seastates.

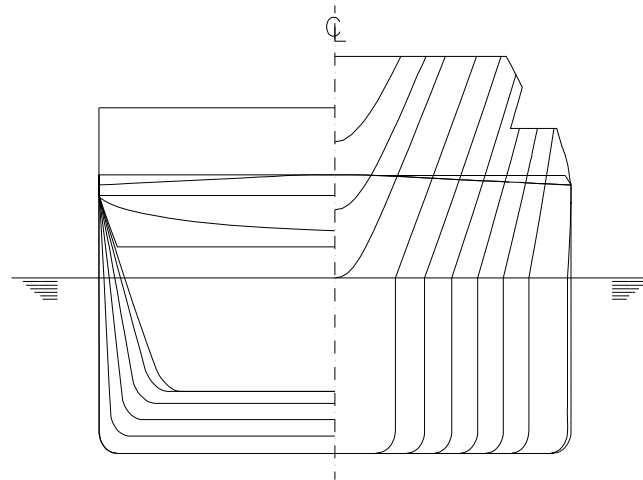
The calculations and the model tests were carried out for a Floating Production Storage and Offloading (FPSO) platform. Figure 12 presents cross section lines. The sides are vertical along most of the ship length. The hull shape is similar to a large tanker ship, although with differences in the stern and the bow lines. The length between perpendiculars of the hull is 280.8m, the beam is 46.0m, and the draught is 16.7m, corresponding to a loaded displacement 174,000ton and a block coefficient of 0.87.

A procedure developed by Clauss et al. (2004) was implemented at the seakeeping basin of the Technical University of Berlin to reproduce deterministic irregular wave traces at a specific target position in the tank.

Fonseca et al. (2010) carried out tests with the FPSO model in regular head waves and measured the vertical motion responses, as well as the vertical bending moment. The authors concluded that the heave and pitch motions are well predicted by the code of Fonseca and Guedes Soares (1998) but the relative motion at the fore end of the bow is slightly under predicted, by around 10%.

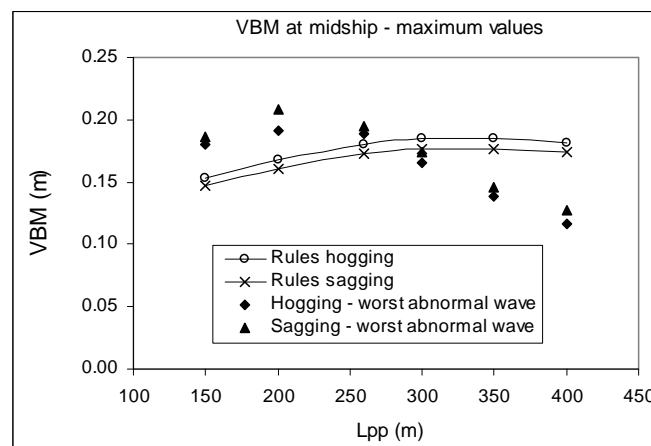
Clauss et al. (2004) and Guedes Soares et al. (2008) investigated experimentally and numerically the wave effects induced by the New Year Wave (NYW) on the platform. The NYW was measured at the Draupner platform in the Central North Sea, when it was struck by a storm from the 31<sup>st</sup> December 1994 to 1<sup>st</sup> January 1995 (Haver and Karunakaran, 1998; Cherneva and Guedes Soares, 2008; Clauss et al. 2008). The investigation of the platform responses to abnormal waves was generalized in Fonseca et al. (2009), where a set of 20

abnormal waves were systematically analyzed. These wave traces were measured during storms in the Gulf of Mexico, Northern North Sea and Central North Sea.



**Figure 12. Bodylines of the FPSO**

Fonseca et al. (2007) investigated the influence of the length of the FPSO platform on the vertical bending moments induced by the 20 abnormal wave records. They have concluded that the moment peaks normalized by the wave height depend of the abnormal wave length and the maximum responses occur for a wavelength of approximately 75% of the platform length. No correlation was found between the maximum induced moment and the steepness of the abnormal waves.



**Figure 13.-Maximum bending moments for the six FPSOs induced by all abnormal waves. Comparison with rules minimum requirements (from Fonseca et al. 2007).**

The calculations were then carried out for a group of six similar FPSOs with lengths between perpendiculars from 150m to 400m. Similar ships mean that the geometric and mass properties are scaled between ships according to Froude scaling.

The authors concluded that the magnitude of the vertical bending moment induced at midship is very much correlated to the relative motion at the bow. In other words, the more the vessel dives the bow into the wave the largest the bending moment. The graph in Figure 13 shows the correlation between the maximum relative motion at the bow and the maximum bending moments induced by all abnormal waves. The results are for the FPSO with 260m between perpendiculars. The correlation is very strong.

### 3. Methods and Tools for Strength Assessment

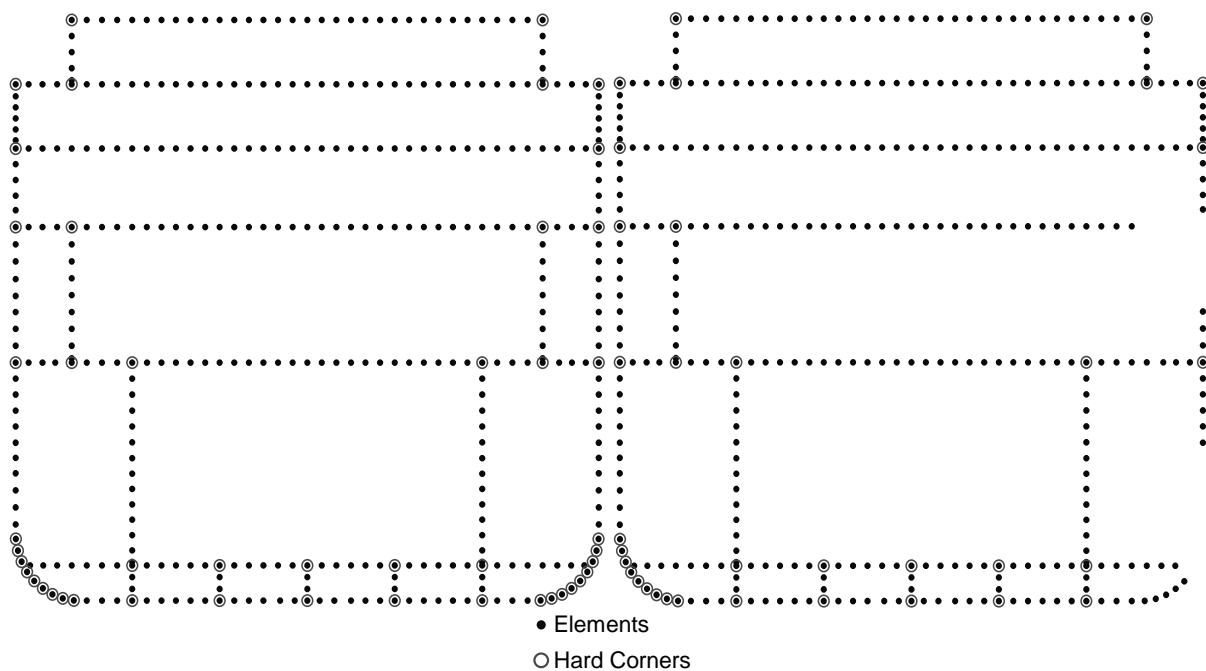
The study of the methods and tools for strength assessment covered the standard finite element analysis and modeling approaches leading to a best practice document on finite element modeling. In addition to static response, also vibratory response and analysis was considered and various studies were made on ship vibration.

The standard strength assessment approaches were considered namely ultimate collapse strength, fatigue strength and impact strength. A more limited activity has addressed as fire and blast resistance of structures as well as hull structural monitoring.

This chapter summarized some work done on benchmark studies related with the ultimate strength of damaged ship hulls and with fatigue strength of welded joints.

#### **3.1 Benchmark Study on the use of Simplified Structural Codes to Predict the Ultimate Strength of a Damaged Ship Hull**

Some studies on the impact of structural damages on the ship ultimate strength have been by. Gordo and Guedes Soares, (2000), Ziha and Pedisic, (2002), and Fang and Das, (2004) conducted using simplified methods based on the Smith's approach to predict the ultimate longitudinal strength of damaged ships. The approach generally adopted in these studies considers that the elements within the damaged area are removed and the ultimate strength of the ship is recalculated using the simplified methods (see Figure 14). However as no validation of this approach had been made an attempt has been made in this project.



**Figure 14- Comparison between the intact section model and the damaged section model for HULLCOLL.**

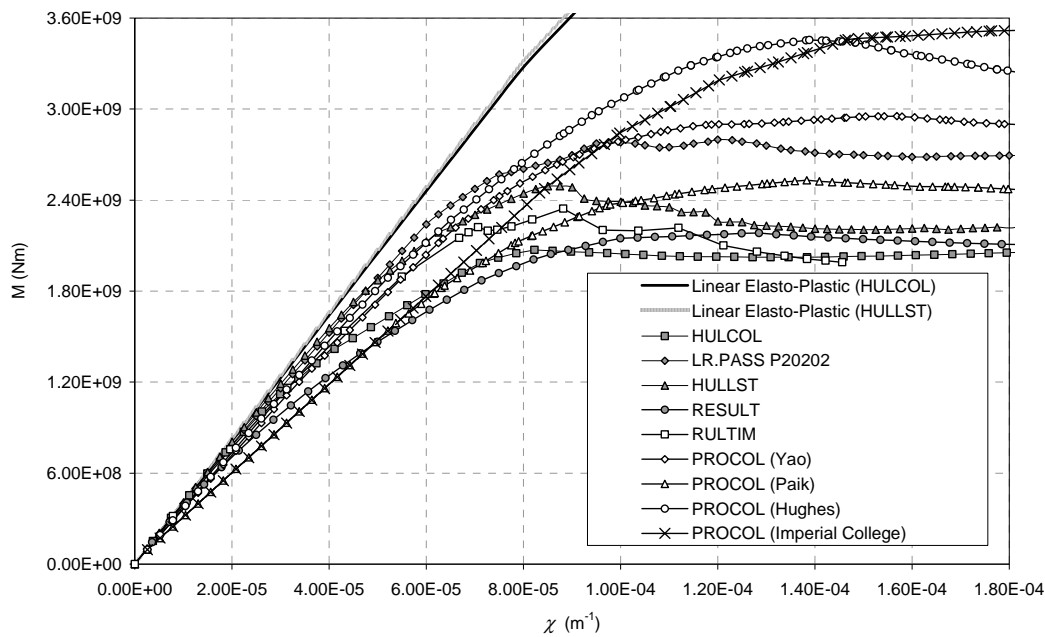
A study was conducted to evaluate the ability of simplified structural analysis methods, based on the Smith (1977) formulation to predict the ultimate strength of damaged ships. Such methods are now widely accepted as a reliable and fast way to obtain the longitudinal strength of an intact ship. The main difference between the methods used in this work and Smith method is that while Smith originally used finite element analysis to derive the stress strain

relationships for the elements, the simplified methods presented here use simplified analytical approaches to derive that relationship.

In order to extend these methods to damaged ships, first a benchmark study on the intact ship was performed in order for the differences between the methods to be evaluated. Afterwards the methods are applied to the same ship section but with damage, which was defined by removing the structural elements from the affected areas. These, in turn, were obtained from a previous study in which a collision was simulated using a finite element model (Voudouris et al. 2000).

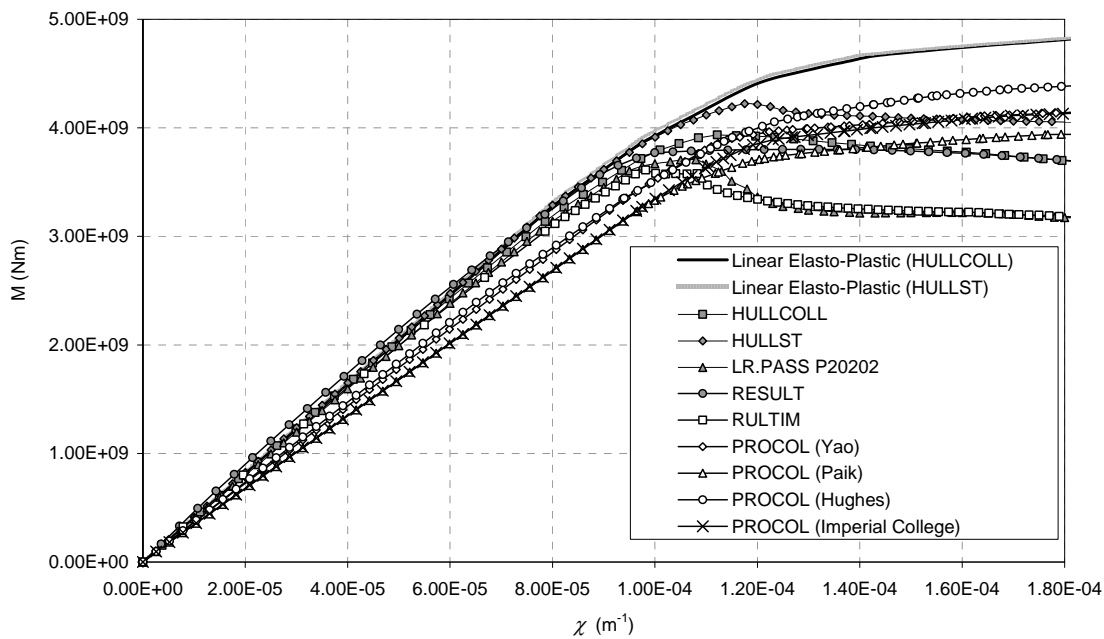
For the damaged ship, the principal axis of the cross-section is rotated comparing to the position of the principal axis for the intact ship. Therefore, strictly speaking, it should be necessary to consider combined bending under the action of the vertical bending moment, contrary to the case of the intact ship where the vertical bending moment induces vertical bending exclusively. However the angle of rotation is small and it is assumed that the principal axes in both cases coincide, even though the cross-section is no longer symmetrical.

In Figures 15 and 16 the moment curvature diagrams obtained by all organizations for the hogging conditions without and with residual stresses respectively are presented. The results obtained with residual stresses have a higher variability in sagging, just as without residual stresses. In the hogging condition the highest differences are around 8% while for the sagging condition the highest differences are around 10%.



**Figure 15- Moment curvature relationship for the hogging condition without residual stresses.**

Note that in hogging it is the structural elements in the lower part of the hull that are compressed: outer and inner bottom, bottom girders and lower parts of the sides and longitudinal bulkheads, while in sagging it is just the opposite, and the decks are compressed. In all procedures applied in the investigation the stress-strain relationship follows the elastic-plastic behavior of material for tension while the differences appear for compression. The substantial scatter of results for sagging indicate that the differences between the applied procedures to evaluate response of stiffened plates are more significant for more thin plating and slender stiffeners rather than plating of moderate thickness and stocky stiffeners typical for the bottom structure.



**Figure 16- Moment curvature relationship for the sagging condition without residual stresses.**

Results obtained for the ultimate strength were compared against each other and with the results of the finite element analysis. Aside from some exceptions, the results of the approximate methods agreed well with each other for the intact and damaged conditions. The simplified methods are more conservative than the finite element analysis in hogging while they seem to give a very good approximation to the result for sagging with some of them overestimating this value.

The simplified methods used in this study compare well with one another for the calculation of the ultimate strength, giving differences that one has come to expect from these types of calculations.

After careful analysis of the ultimate moment it seems that the results present a higher variability in predicting the sagging moment rather than the hogging moment. One should take this in consideration because the strength in sagging is usually the critical condition of ship hulls.

For the damaged ship, the finite element method seems to overestimate the mean value of the simplified methods in hogging. While in sagging it gives a closer value to the mean than the simplified methods themselves. However without experimental analysis it is impossible to say which method is more precise. Therefore this conclusion holds just for the specific case found in this study and it is not possible to say which results are less conservative because it is possible for it to be overestimating the actual resistance of the ship.

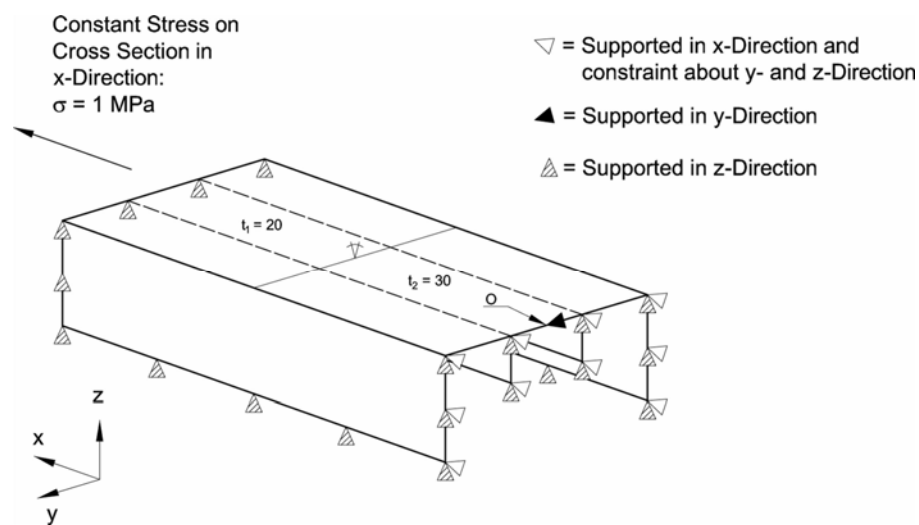
Considering the fact that no experimental analysis has been performed, one cannot say if the simplified methods are in fact a useful tool to calculate the resistance of damaged ships. However, considering that simplified methods are accepted as reliable tools for calculating the ultimate moment of intact ships even with the differences shown in these results, and that the results obtained for the damaged ship do not present bigger differences than the intact condition. Then, it is possible to say that, simplified methods compare well between each other for the calculation of the ultimate bending moment of damaged ships.



### 3.2 Benchmark Study on the Analysis of Fatigue in Joints

A round robin was performed regarding the computation of structural hot-spot and notch stresses for fatigue assessment. Three details were analyzed by several groups:

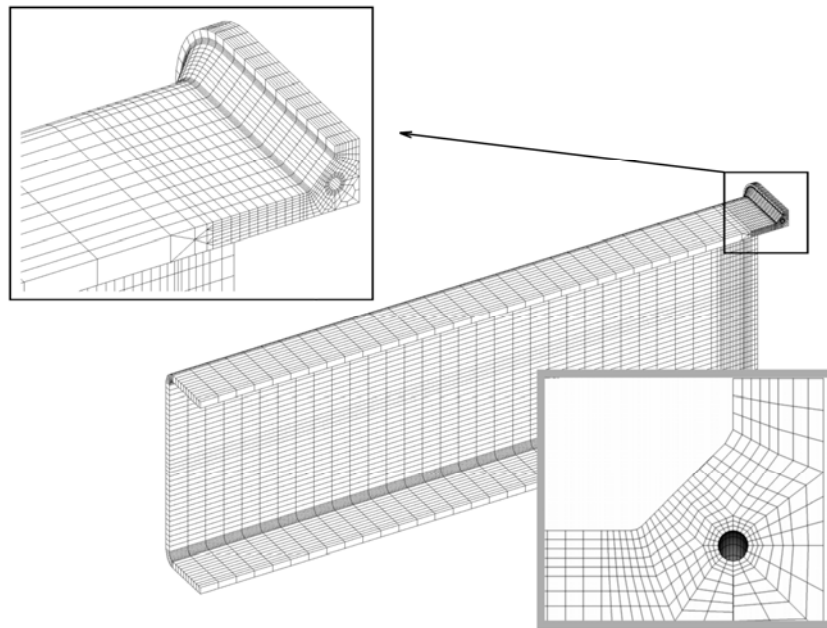
- Thickness step at a butt joint maintaining the moulded line so that secondary bending is present under axial loading (5 groups). Figure 17 shows the situation investigated representing the upper deck of a container vessel, where the deck thickness is increased from 20 mm to 30 mm, e.g. in the vicinity of a hatch corner (not included in the model). The stress increase factor due to secondary bending at the weld toe is here approx.  $K_s = 1.6$ , which can be well computed with shell and coarse solid models. The deviation between the results of the partners was hence small lying between +5% and -3%.



**Figure 17- Simplified model for the deck strip of a container ship with thickness step**

- Penetration of a longitudinal (T-bar) through a bulkhead (5 groups) with two variants, one conventionally closed with overlapped patches and the other with a T-slotted web. The fatigue-critical point was the connection between the flange and the web or patch, respectively, as well as the end of the stiffener on the flange. Structural hot-spot stresses were analyzed.
- Fillet-welded end of a rectangular hollow section subjected to axial and bending loads (3 groups from MARSTRUCT + 4 groups from International Institute of Welding). Figure 18 shows a quarter model with half of the hollow section (left), a vertical intermediate plate (right) and the fillet weld connection. Fatigue tests have shown weld root cracking so that the round-robin concentrated on the notch stress in the weld root, which was fictitiously rounded with a radius of 1 mm acc. to IIW recommendations. Table 2 shows some modeling details and the resulting elastic notch stresses. The differences between the results of the partners are quite small except for partner G where automatic meshing has created few elements with relatively long edges in the radial direction at the stress peak, i.e. in the direction of the largest stress gradient. These forced the local stresses to smaller values. Without these results the coefficient of variation is 2-3%.

The results of the round robin are published in Fricke, et al. (2008). In addition, they led to the development of a procedure for the fatigue assessment of fillet welds subjected to throat bending based on a structural weld stress (Fricke and Kahl, 2008).



**Figure 18- FE model of fillet-welded rectangular hollow section for notch stress analysis**

**Table 2: Analysis results for hollow section joint (for nominal stress of 100 MPa)**

Participant	Program	Element Type (Displacement function and shape)	Element length along circumference	Maximum notch stress [MPa]	
				Tensile LC	Bending LC
A	ANSYS	quadratic (hexahedral)	~ 0.1 mm	888	637
B	ANSYS	quadratic (hexahedral)	~ 0.25 mm	867	601
C	ANSYS	quadratic (tetrahedral)	~ 0.4 mm	913	650
D	ANSYS	quadratic	Not reported	907	642
E	I-DEAS	quadratic (hexahedral)	~ 0.45 mm	914	644
F	ANSYS	quadratic (tetrahedral)	~ 0.2 mm	864	620
G	ANSYS	quadratic (tetrahedral)	~ 0.3 mm	700	600
Coefficient of variation (all results)				8.7%	3.3%
Coefficient of variation (all results without G)				2.5%	2.9%

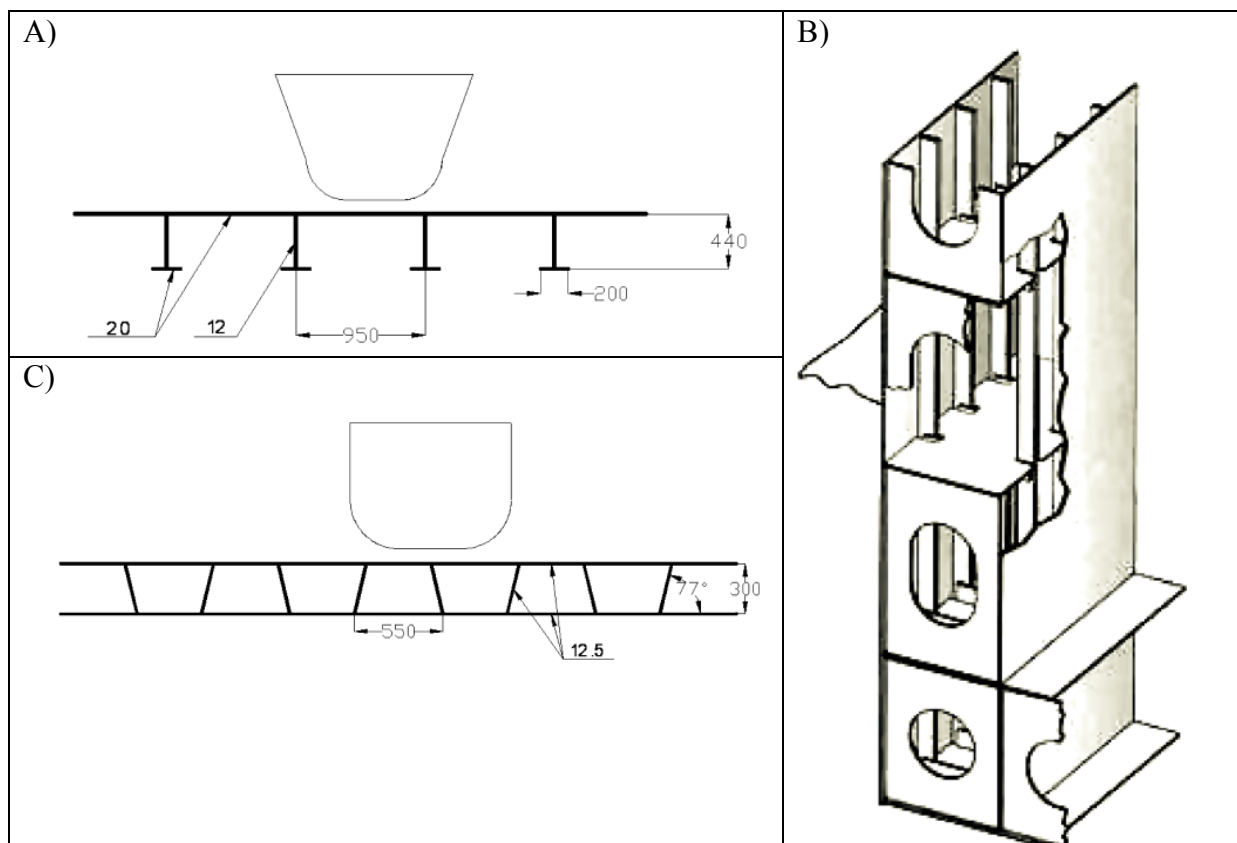
Another round robin on fatigue assessment was performed. Three details were proposed, but only the first one was analyzed by five groups. It concerns load-carrying fillet welds at doubler plates and lap joints which were also fatigue-tested (see section 4.3). Here, the non-fused root face is parallel to the loading direction so that crack initiation is possible at the weld toe as well as weld root.

A 2D analysis is sufficient here. Different approaches have been applied, including the structural hot-spot stress approach, the structural approaches according to Xiao and Yamada, to Dong and to Poutiainen and the effective notch stress approach. The approaches and first results are published in Feltz and Fricke (2009). The round robin revealed several aspects to be considered in the analysis. These were taken into account in rules and recommendations such as Fricke (2008).

### **3.3 Benchmark Study on Collision Resistance Simulations of Ship Structures**

Due to safety assessment of ships, numerical simulations on ship collisions and groundings are performed increasingly more often. Accuracy of these simulations is crucial when the structural design and optimization for crashworthiness are considered. Therefore, while load task discussed the mechanics of ship groundings as influenced by the material and structural behavior, the task on structural resistance of ship structures analyzed the methods to assess collision resistance of the steel structure; thus it concentrated on the internal mechanics.

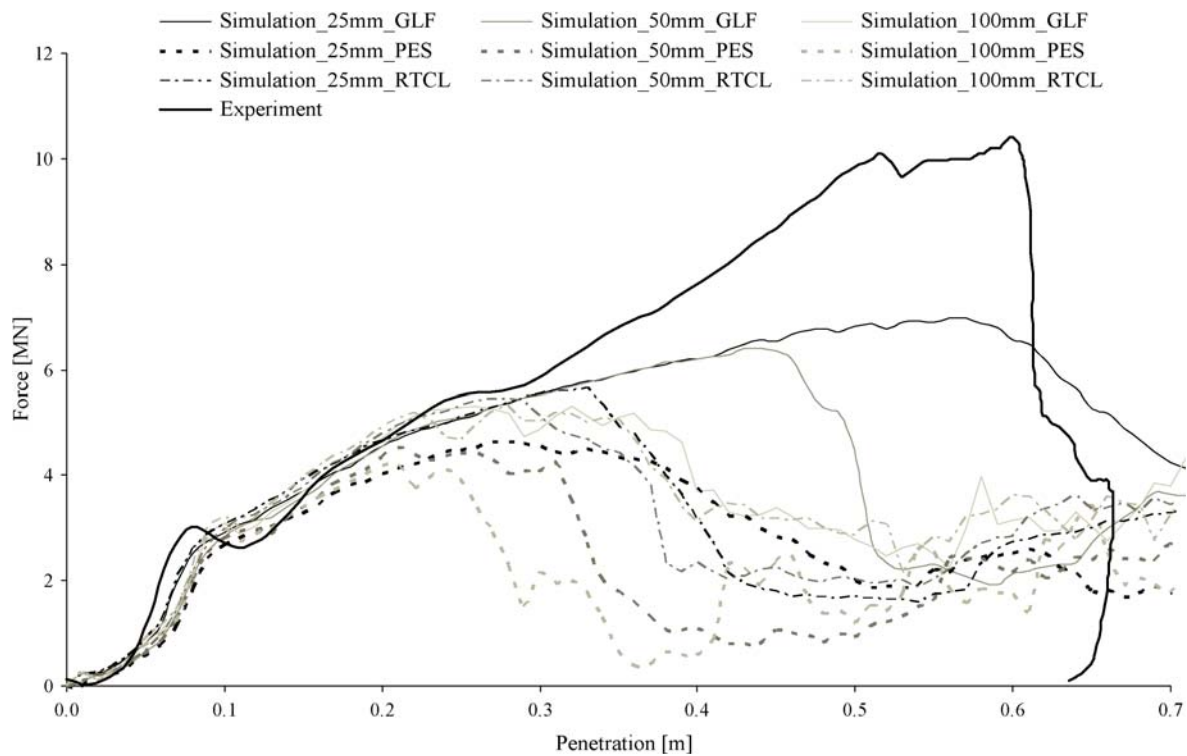
A benchmark was set up where stiffened plate, steel sandwich structure and side structure of a ship (see Figure 19) were analyzed by different institutions using the same finite element mesh and software, and material data, but different material relations until failure



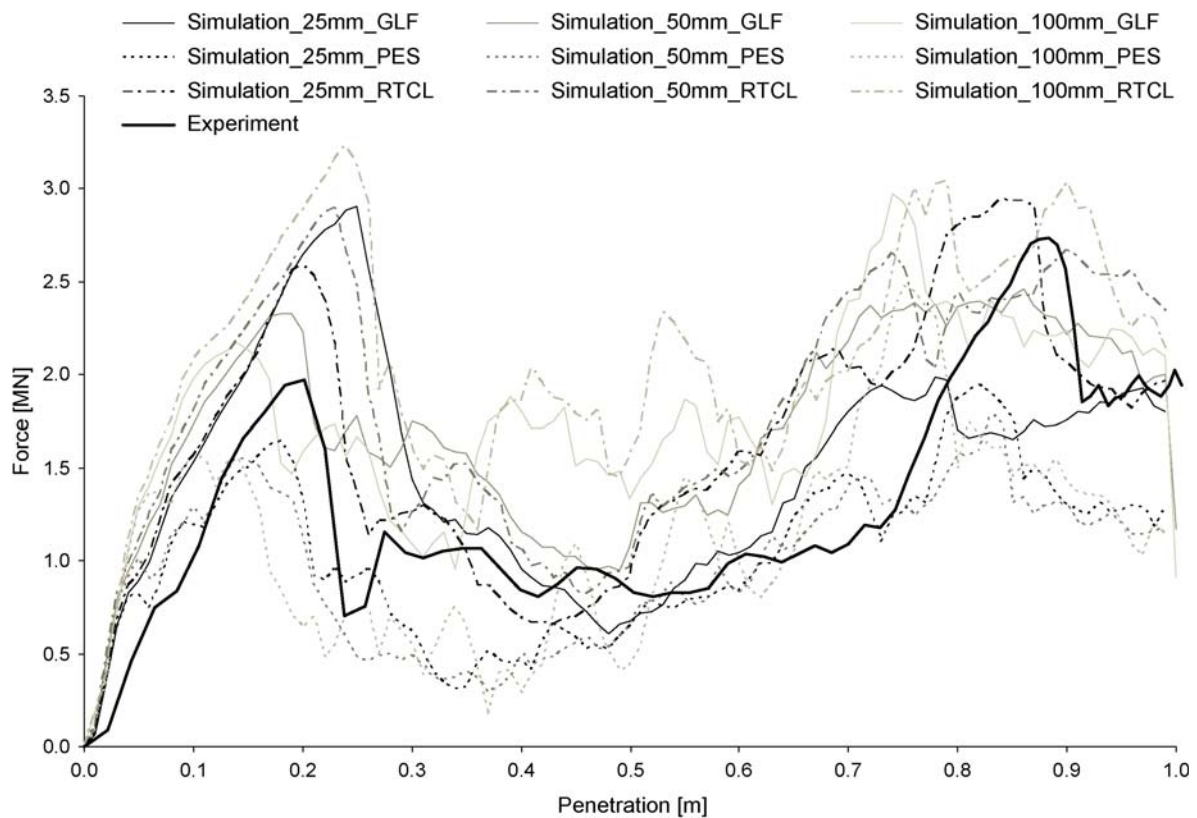
**Figure 19 – Geometries considered in the benchmark (Ehlers et al., 2008).**

. The aim of the investigation was to reveal the differences at structural level between the failure criteria proposed by Germanischer Lloyd which is based on thru-thickness plastic strain, the criteria by Peschmann and the RTCL (Rice-Tracey and Crockcroft-Latham) criteria. The numerical simulations were compared with the full-scale collision tests

performed during 1997 and 1998 in Netherlands. The investigation is described in depth in Ehlers et al. (2008).



**Figure 20 – Stiffened plate comparison (Ehlers et al., 2008).**



**Figure 21– Side structure comparison (Ehlers et al., 2008).**

The benchmark study considered three different mesh sizes, i.e. 25mm, 50mm and 100mm. The crack initiation and propagation were modeled in LS-Dyna using the element deletion option. Calculations were performed quasi-statically in displacement control, recording the introduced force; the rigid indenter having the shape of bulb was moved with constant velocity. The boundary conditions at model edges were considered clamped at all four edges. Figures 20 and 21 show the comparison between the simulations and experiments for the stiffened plate and the ship side structure.

Figures 20 and 21 show that the Peschmann and RTCL criterion correlate well when the parts where the failure is not yet occurring. The general trend is that the failure is predicted too early for section 1 and while Peschmann criterion works well and RTCL criterion overshoots the force penetration curve for section 3. The results indicate that for coarser meshes (in present case 100mm) the deletion of elements has higher influence than for the finer meshes (25mm and 50mm). Therefore, mesh refinements should be considered in coarse mesh collision simulations. It is also concluded that the mesh size sensitivity might be more important than the material model when the collision simulation accuracy is concerned. Therefore, unified mesh sensitivity equation should be considered, a proposed after the benchmark by Ehlers and Varsta (2009).

## **4. Experimental Methods for Strength Assessment**

### **4.1 Test on mild steel box girders subject to pure bending moment**

The evaluation of the ultimate capacity of ships under bending moment is a very important issue on the structural design of ship structures, as it is associated with a global failure of the hull and the final result is normally the loss of the ship, its cargo and human lives.

A series of tests were profound to describe the strength of box girders under pure bending moments. The first series of tests intends to compare the ultimate bending moment of box girders made of mild steel (Gordo and Guedes Soares, 2008) with a similar series of tests using very high tensile steel and performed under the EU project FasdHTS (Gordo and Guedes Soares, 2009). These tests allow verifying the increase on the structural efficiency by using high tensile steel and, also, to establish the dependency of the ultimate bending moment due to the variation of the column slenderness of the stiffened panels which are primary elements of the box girders and ship structures. The variation of column slenderness was obtained by having different frame's spacing in each box girders, where the slender one has twice the slenderness of the stockiest one.

The test set up for 400mm frame spacing box girder is presented in Figure 22 and it is a typical four point loading test.

The tests showed that the performance of the box girders are as expected and the performance of the high tensile steel model is very good obtaining a global efficiency of 2.28 while the maximum available is 2.56 due to the difference of the yield stress of the two different materials employed. The lower value results from the effect of the increase on the column slenderness of the panel under compression when the yield stress of the material increases.

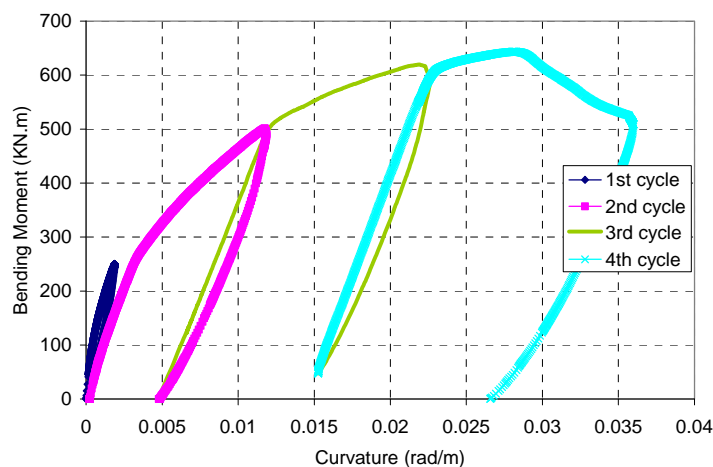
The column slenderness controls the type of collapse of the structure: high column slenderness leads to more sudden collapse, follow by large discharge of load during the failure of the structure. That was found during the experiments and it is represented by the shedding pattern of both experimental moment curvature curves.

Residual stresses are very important in this type of experiment and the moment curvature curves depend very much on their level according to the manufacturing process. However it is possible to have a good understanding of the behavior of the structure without residual stress by performing a series of loading cycles prior to the collapse of the structure. With those cycles one removes the residual stresses on the panels in tension allowing for the observation of the elastic behavior of the structure, Figure 23. However the residual stresses in the panels

under compression cannot be removed with this technique, which explains the low tangent modulus near the maximum bending moment.



**Figure 22 – Setup of the test on a mild steel box girder with 400mm frame spacing**



**Figure 23 – Moment curvature relationship for 200mm frame spacing box girder.**

#### **4.2 Corrosion-Dependent Ultimate Strength Assessment of Aged Box Girders**

A corrosion-dependent analysis of the ultimate strength analysis of aged box girders based on experimental results is presented here. Three multispan corroded stiffened box girders subjected to four-point vertical load are analyzed, idealizing the behavior of midship sections of full ships. The specimens have three levels of corrosion.

##### ***4.2.1. Experimental set up of corrosion deterioration***

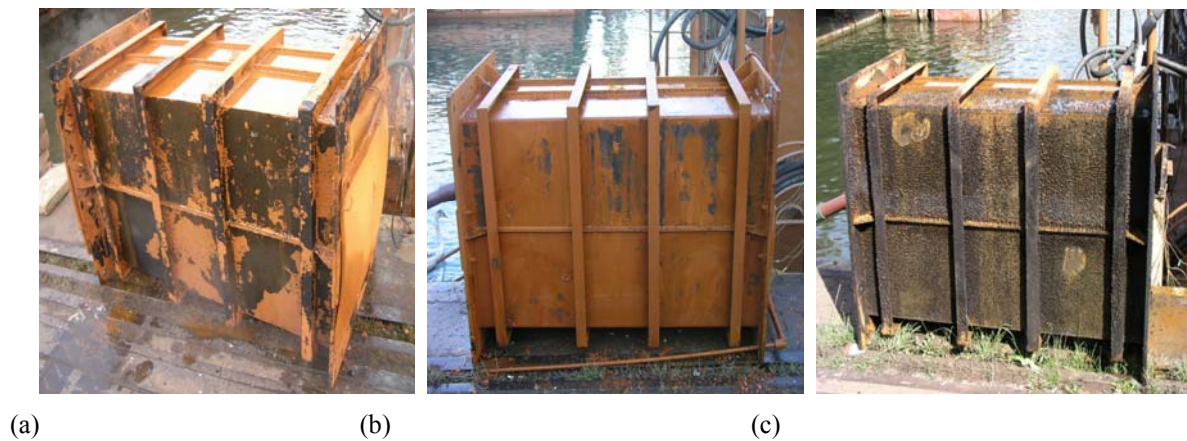
Three specimens, in the form of box girders representing a midship section of ship hull have been tested in a corrosive environment in direct contact with seawater. The dimensions of the specimens are 1400 x 800 x 600 mm. The box girders are made of steel of minimum yield point equal to 235 MPa and the Young modulus of 206 GPa. The specimens were exposed to



Baltic seawater without any corrosion protection system (no coating). One of the box girders was tested in cold water and the others in hot water. The box girders were placed in large tanks and seawater was continuously pumped into the tanks. The temperature of the seawater was increased and the oxygen depolarization sub process rate was increased by agitation of the seawater, which resulted in the corrosion rate increase.

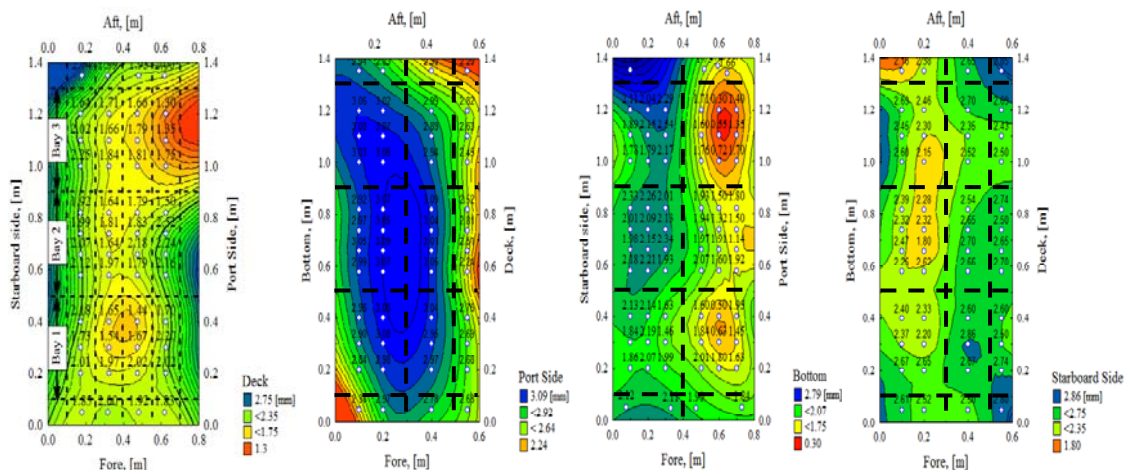
To model corrosion rate acceleration, anodic polarization of the metal surface was used. Anodic electric current was supplied by an external source. The test durations were 30 days for experiments with application of external electrical current and 90 days for the test performed without polarization. The models were cleaned of corrosion products once a week.

Figure 24 (a, b) shows the box girders after test with anodic polarization and exposure to hot and cold sea water and the box girder tested in hot water without polarization is shown in Figure 24(c). Detailed information about the corrosion set up is presented in Domzalicki et al, (2009).



**Figure 24-Box girders after tests in hot and cold sea water with and without polarization (Domzalicki et al, 2009).**

A survey of corrosion thickness on the three corroded box girders plating was analyzed. The corrosion data consists of 636 measurements of corrosion thickness, with 212 measurements collected for each box girder. The as built thickness of measured plates and stiffeners are 4.5 mm. As can be seen from Figure , the corrosion distribution is non-uniform and several places are subjected to aggressive corrosion deterioration as can be observed.



**Figure 25- Plating thickness, severely corroded box (Saad-Eldeen et al, 2011a)**

Experimental evidence of corrosion, reported by various authors, shows that a nonlinear model is more appropriate than a linear one. The mean value of the measured corrosion depth of the deck plates (0.41, 2.31 and 2.62 mm) of the box girders are compared with the upper limit of the 95 percent confidence interval of the corrosion depth defined by the regression equations developed in (Guedes Soares and Garbatov, 1999), for deck plate of ballast tanks of real tanker ships, reveals that the initially corroded box matches the 0.2 year of deterioration, while the moderately and severely corroded boxes are related to 17.9 and 23.3 years of deterioration, respectively, considering that the coating life is 0 year (Saad-Eldeen et al, 2011a).

#### 4.2.2. Experimental set up of ultimate strength test

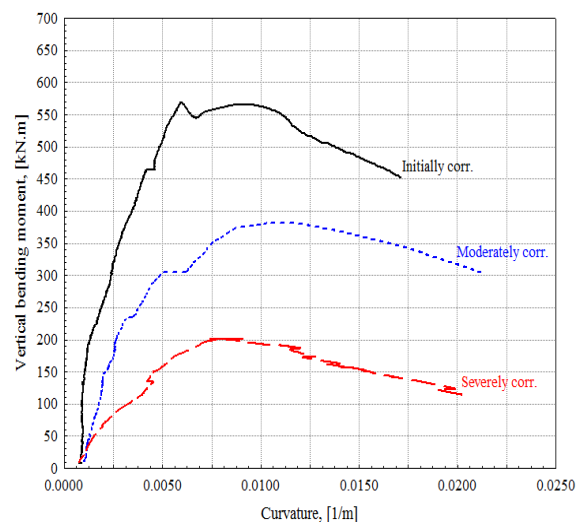
Three ultimate strength tests have been carried out for three corroded stiffened box girders. The use of multiple bays instead of a single bay allows having results that are more realistic by avoiding the effect of the boundary conditions for the central plates, which is due to the eccentricity of load and the interference between adjacent panels.

The box girders have been mounted between two stiff supporting arms using bolt connections. The box girder was subjected to four-point vertical bending moment, in an arrangement similar to the one described in section 4.1. The bottom part is subjected to tension and the upper part, deck, is under compression. The bending moment is kept constant along the box girder, between bolt connections. There are four points for transmitting the load, two are located at the supports of the arms and two are on the boundary between the box girder and the supporting arms. More detailed information is given in (Saad-Eldeen et al, 2010; 2011a; 2011b).

The experimental results of the ultimate bending moment of the tested box girders are given in Table 3 and Figure 26, which show the moment-curvature relationship.

The moment-curvature relationship is linear until the occurrence of buckling or yielding. For the tested box girders, it is noticeable that as the corrosion level increases, the linear range becomes less and the material nonlinearity starts to take place under smaller loads, which gives an indication about the effect of corrosion on the geometrical and mechanical properties.

As may be seen in Figure 26, the slope of the three curves is different, which accounts for the effect of corrosion degradation on the structure flexural rigidity, which directly affected the ultimate bending moment capacity of the box girders.



**Figure 26- Moment-curvature relationship (Saad-Eldeen et al, 2011c).**



By comparing the response of the three box girders in the linear region, it is evident that as the corrosion level increased the curvature also increases for the same bending moment. As a result of the moderate and severe corrosion degradation, the ultimate bending moment that the box girder can withstand decreases by 32.87% and 64.67%, respectively.

The section modulus reduction of the moderate and severe corroded box girders with respect to the initially corroded one is 32.81% and 47.93%, respectively. The section modulus reduction is different in comparison to the ultimate bending moment reduction. This is explained with the non-uniform corrosion degradation distribution, the changes in mechanical properties, and the reduction of the residual stresses (Saad-Eldeen et al, 2011c).

**Table 3-Ultimate bending moment-curvature**

<b>Box</b>	Bending moment, kN.m	Curvature, 1/m	<b>%</b>
Initial	568.942	0.0059	<b>100</b>
Moderate	381.9777	0.011	67.13
Severe	201.0058	0.0075	35.33

It has been seen that for any box girder, after passing the level of the ultimate bending moment, the curve starts to go down with an increase of the curvature (see Figure 26). This may be explained by the fact that the reduction of the capacity of the structural members result in a very large deformation. The final collapse modes for the three box girders after the test are presented in Figure 27.



**Figure 27- Final collapse mode for initially, moderately, and severely corroded box girders (Saad-Eldeen et al, 2011c).**

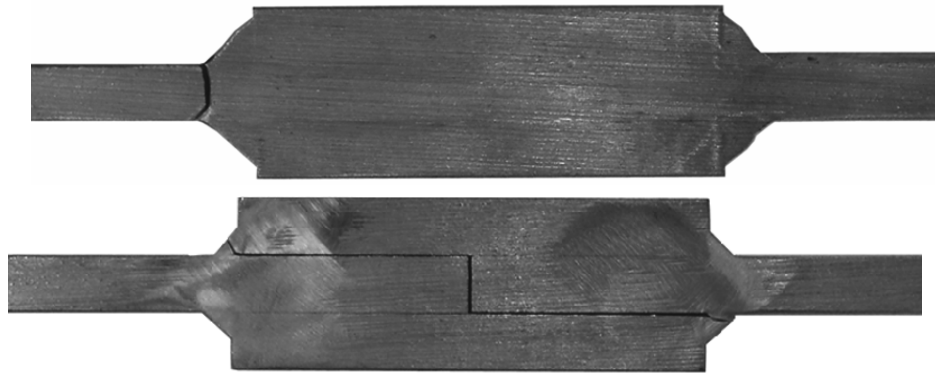
### **4.3 Fatigue Tests**

Remarkable fatigue tests related to ships were reviewed and some additional tests were performed in order to

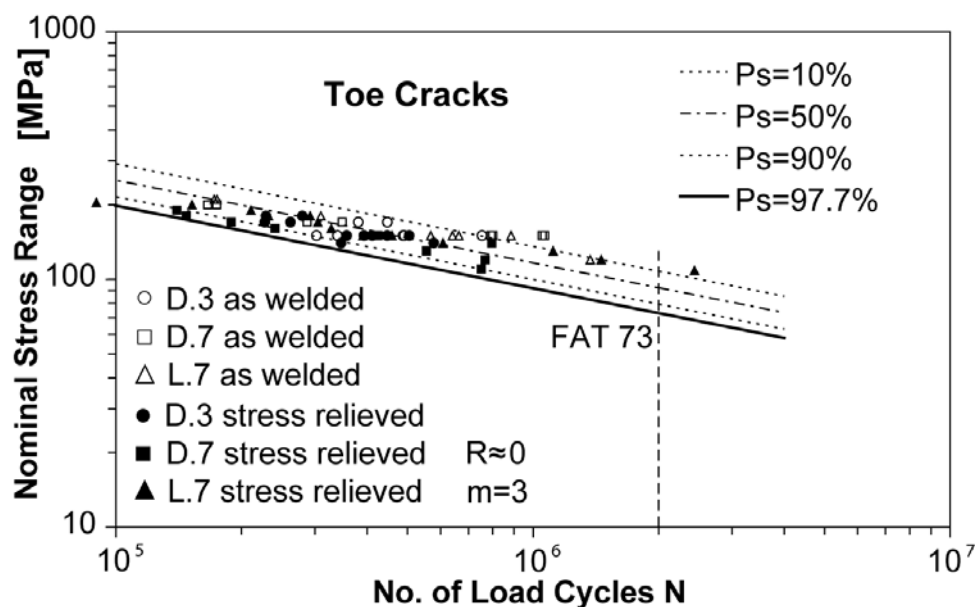
- support the round robin fatigue analyses performed and partially discussed in section 3.2 here, with data for verification purposes
- clarify some open questions in parallel running research projects. These include the residual stress measurements to show how far these could have affected test results.

The fatigue tests were performed on small-scale specimens and components under constant amplitude loading, yielding S-N curves after statistical evaluation. In particular the investigations on following details are notable:

- Fillet-welded ends of rectangular hollow sections subjected to axial and bending loads. These showed weld throat bending and crack from the weld root so that they can generally serve for benchmarks on fatigue assessment approaches considering local stresses in fillet welds. The results are published in Fricke et al. (2006)
- Load carrying fillet welds with loading parallel to the non-fused root faces, occurring e.g. at doubler plates and lap joints. Depending on the throat thickness, fatigue cracks may initiate from the weld toe or the weld root (Figure 28). The correct prediction of the crack initiation site and fatigue strength is a challenge to all fatigue assessment approaches. The test results are shown in Figure 29 and Figure 30 and are published in Fricke and Feltz (2010) and Fischer et al. (2011)
- Joints of bulb flats welded either with a butt-weld filling the whole bulb or with a patch on top. The quality including misalignment affects the fatigue behaviour so that it must be considered during the fatigue assessment. The investigations are published in Notaro et al (2007)



**Figure 28- Investigated doubler plate specimen (top) and lap joint (bottom) with fatigue cracks at upper left weld**



**Figure 29 S-N results for doubler plates (D) and lap joints (L) with 3 and 7 mm throat thickness (Frick and Feltz, 2010)**

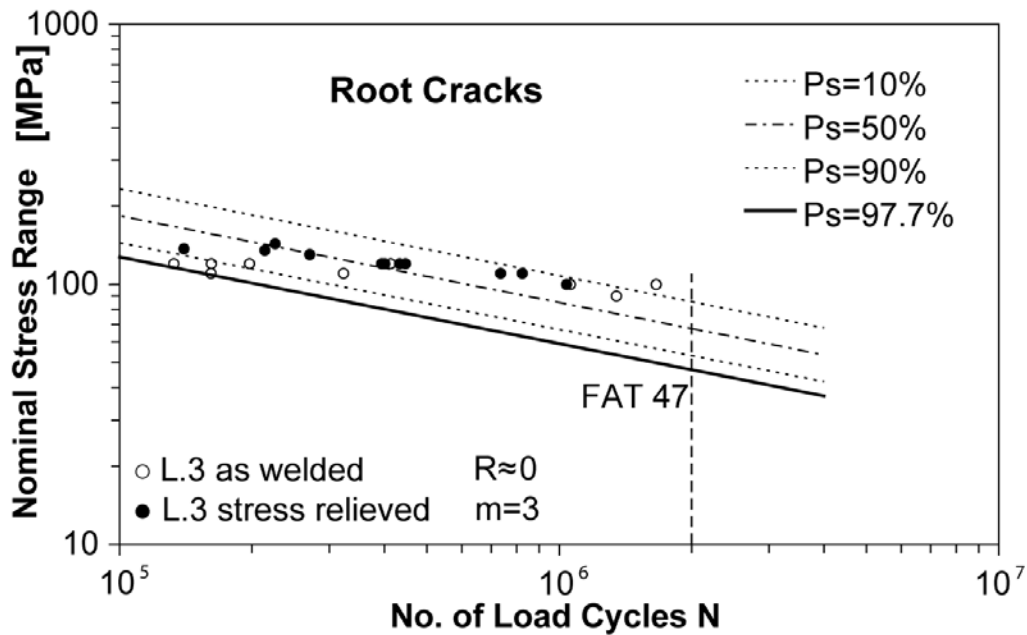


Figure 30-S-N results for all lap joints with 3 mm throat thickness (nominal stress refers to main plate section) (Fricke and Feltz, 2010)

## 5. Methods and Tools for Structural Design and Optimization

The shipbuilding industry usually deals with small series of very large structures with a life-cycle of 20 or 30 years; this means that design choices have an impact which may last for several years and makes design a very critical phase, further complicated by other factors such as:

- the huge volume of data to manage;
- the massive data exchange with many sub-contractors, suppliers and stakeholders;
- the potential significant cost savings both in the building phase and during the whole lifecycle of the ship (repair, maintenance, ...) made possible by design optimization;
- the strong connection and interdependency with the production process, in a concurrent engineering perspective.

Therefore it is important to have efficient procedures for ship design, among which optimization techniques: these procedures are oriented to structural analysis but also address other multi disciplinary design tools, such as CAD/CAM systems, Classification Societies rule sets, CFD and seakeeping software tools, etc.

During the MARSTRUCT project, the aspects related to both preliminary and detailed structural design have been considered and investigated by identifying, selecting, sharing and improving the existing and available methodologies and tools. Efforts have also been devoted to extend the investigation towards those aspects, such as production and maintenance implications, which more and more are assuming an important role on some decisions taken in the design phase.

The summary reported in this paper describes the *highlights* of the work, with specific reference to three benchmark activities:

1. simulation and optimization of the ship production process;
2. global optimization in the early design phase of a fast ferry;
3. structural optimization of the mid-ship section of a fast ferry.

### **5.1 Benchmark on simulation and optimization of the ship production process**

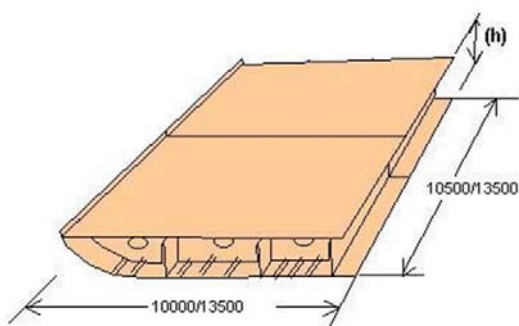
Production simulation is a powerful technique able to analyze different types of problems and to manage and optimize the production for different time horizons. A benchmark was carried out in the most common use of simulation: the calculation of fabrication time and cost of a ship building block, which is usually one of the steps necessary to set up an efficient production schedule.

In broader terms, production simulation has other applications and can be used for different purposes:

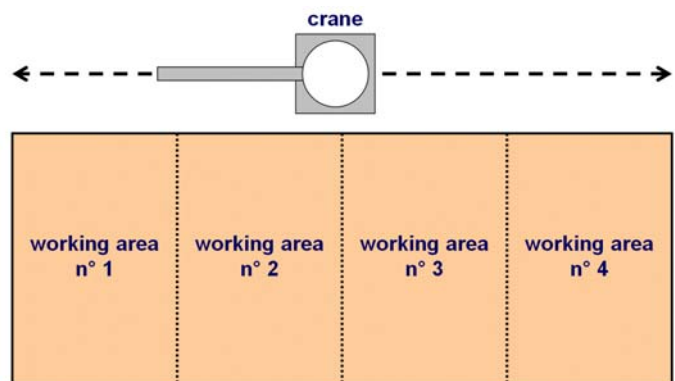
- workshop design:
  - machines/equipment (position, number, capacity, etc.);
  - simulation before investment (make or buy decision);
- definition of production schedules:
  - validation of production plans;
  - decrease of the lead time (identification of bottlenecks);
  - definition of the best production ordering (sequencing);
  - optimization of space allocation in the shipyard;
- production management:
  - balance of the workload (improved personnel and resource planning);
  - improved material management;
  - impact of machine failure;
  - impact of workload and workforce variations.

Nevertheless, in most cases, the purpose of the simulation is to develop the best production strategy by playing on levers such as the distribution of tasks on different work areas, the fabrication sequence within each zone and the quantity of resources used (mainly the number of workers).

In this benchmark, based on a common and agreed specification, two simulation models were independently developed using two different commercial software tools: EM-Plant and Arena; they simulated the production and pre-outfitting process of two consecutive bottom blocks of a ship side in a virtual shipyard with 4 building areas and one single crane (see Figures 31 and 32).



**Figure 31 ship portion to build**

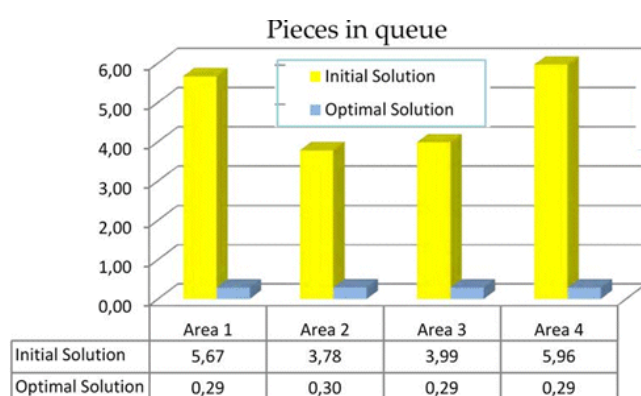


**Figure32- shipyard layout**

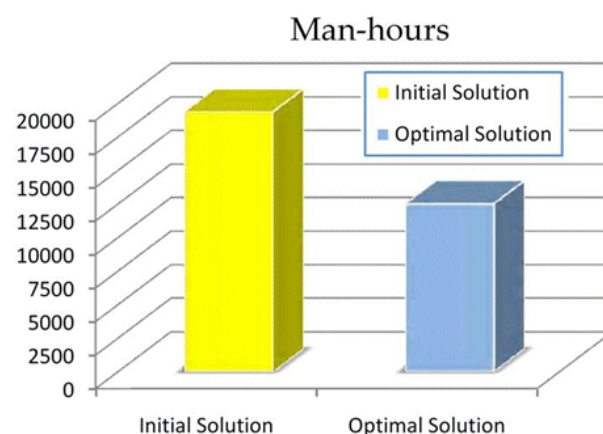
Even with some different assumptions in the representation of particular aspects of the activity of the workers and of their shifts (two per days, 8 hours each), the two approaches led to consistent results, in terms of resource utilization, lead time and number of pieces in queue. As a matter of fact, the total production time calculated by the two groups was 92.8 days and 88.5 days, with a difference of only 4.7%.

In the second phase of the activity, the two partners decided to implement an optimization problem in order to increase the efficiency of the production; thank to the consistency of the results of the comparative phase, the two partners, in order to explore a wider range of solutions, implemented two completely different optimization strategies, consisting in different ranges for the number of workers (carpenters, plumbers, welders), different launching sequences and different constraints on the maximum number of workers per activity.

A certain number of runs were performed, leading to very different (but equally interesting) sets of results; a minimum production time of 49.7 days was reached by one model, while the other led to two solutions, the first with the minimum production cost and a production time of 71.4 days and the second with the minimum production time of 63.6 days. All optimized solutions were characterized by a workload more balanced and a dramatic reduction of pieces in queue as shown in the example results of Figures 33 and 34.



**Figure33– Pieces in queue**



**Figure34– Total man-hrs**

## **5.2 Benchmark on global optimization of a fast ferry**

A collaborative study was performed to define and validate an innovative methodology for ship design based on an extensive use of optimization techniques, which was applied to the design of a fast-ferry. The methodology consists in a two-level and multidisciplinary optimization. The first level (global level) consists in modifying the ship overall dimensions to reach a global objective. The second level (local level) allows for the definition of the successive designs with a local optimization of each iteration.

The methodology is based on an iterative process built around three tools operated in interaction. A naval architecture software tool is used to generate the ship model at each step of the global optimization and to assess the model (evaluation of hydrostatic properties, ship weight, hull stability, hull resistance, etc.). The midship section of each global iteration is defined and optimized according to Rule constraints with a dedicated tool, with an objective

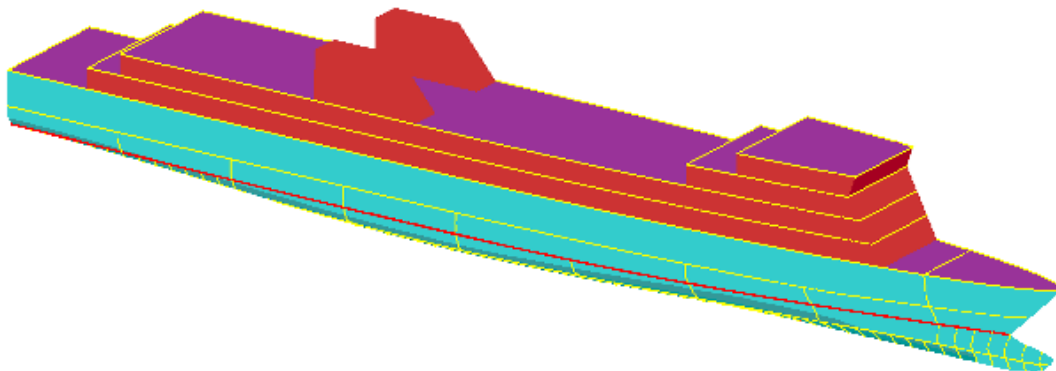
of least weight. The overall process is hosted by modeFRONTIER, which coordinates the tools and performs the global optimization.

ModeFRONTIER is a general purpose optimal design tool developed by ESTECO, able to deal with multidisciplinary problems. It is a state-of-the-art PIDO tool (Process Integration and Design Optimization) that offers a large number of functionalities in terms of process integration, design optimization and post-processing analyses.

The naval architecture calculations were performed by AVPRO. Based on a parametric model, AVPRO can define and assess a 3D model of the ship with a minimum amount of data, in order to comply with the short duration of early design.

The structural optimization of the midship section was performed by LBR5, which performs a 3D structural analysis of a ship portion (usually the midship section), and a scantling optimization of the structural elements (plate thickness, size and spacing of the longitudinal and transversal members), based on different objective functions, as higher inertia, less weight and/or lower cost.

In order to demonstrate the possibilities offered by the two-level and multidisciplinary optimization, the methodology was applied to a fast ferry. The design of a 150 meter long, 7500t displacement ship, accommodating 400 meters of garage truck capacity at a service speed of 30 knots was initiated with AVPRO (Figure 35).



**Figure 35 – Case study (fast ferry)**

The hull resistance was selected as the objective function to minimize. Restrictions were defined for the optimization: minimum garage length (400 meters), correct balance of the ship, basic stability checks.

The two-level and multidisciplinary optimization problem was defined as follows. The first level (global level) consisted in modifying the ship model overall dimensions to reach a global objective of minimal hull resistance, keeping a specified minimum garage length, and considering some feasibility restrictions. The waterline length, waterline beam and draught were the design variables of the global level optimization.

The objective of the second level optimization (local level) was to define an optimal structural design for each global iteration, minimizing the structural weight and complying with standard strength Rules, modifying the scantlings of the midship section (plate thickness and stiffener dimensions and spacing).



**Table 4– Results of the two-level optimization**

	Initial Design	Best design
Length (m)	150	152
Beam (m)	20	18.8
Draught (m)	5	4.3
Parking length (m)	440	421
Propulsion power at 30 knots (kW)	21 400	16 700

The results obtained for the initial design and the final optimized design are summarized in Table 4. The optimization led to a decrease of 22% of the required propulsive power, complying with all the criteria (vehicle capacity, stability requirements, Rule structural requirements).

The study brilliantly demonstrated the validity and feasibility of an approach based on optimization techniques, and on the interoperability of different tools.

### **5.3 Benchmark on structural optimization of the mid ship section of a fast ferry**

A benchmark on a classical scantling optimization problem was defined and developed by 5 groups. The object of the study was the mid-ship section of a deep-V shaped mono-hull fast passenger-car ferry made of aluminum alloy (FINCANTIERI MDV 1200).

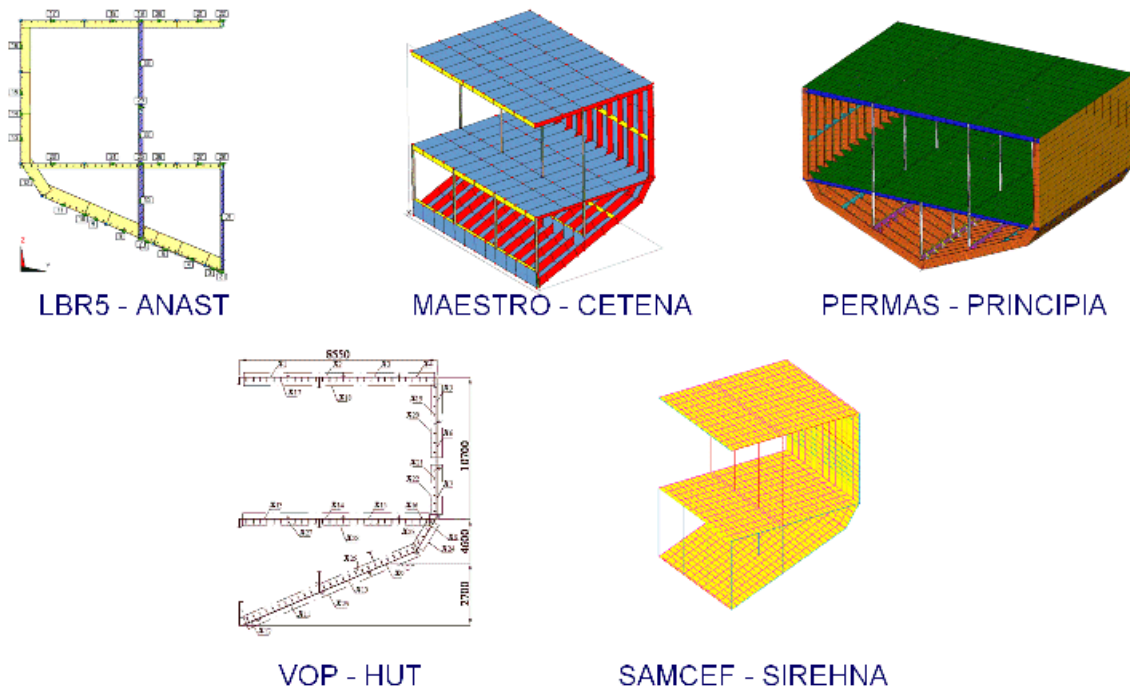


**Figure36– Fincantieri MDV 1200 vessel**

Four Rule loading conditions (DNV HSLC 2005) were used, together with a set of 11 design variables and other constraints, such as admissible bending and shear stresses on shell plating and extruded profiles; the objective function was the minimum weight.

The problem of structural optimization was approached in this benchmark with different techniques using a wide range of codes: specialized codes for marine technology, such as MAESTRO and LBR5, general purpose FEM programs, such as PERMAS, general purpose optimizers coupled with FEM codes, like modeFRONTIER with SAMCEF, and the advanced optimization techniques, such as vectorization coupled with genetic algorithms (VOP). An overview of the structural models used can be seen in Figure .

Due to code constraints, these approaches have a different number of hypotheses, not all of them coincident with those defined in the benchmark specifications. For example, MAESTRO has its own comprehensive failure criteria, and does not allow users to define their own. On the other hand, generic FEM codes, while they may give more flexibility in the definition of criteria, do not allow the user to easily define the stiffener spacing or their number as a variable. Finally, the analyses based on genetic algorithms have the maximum flexibility but also the greater degree of abstraction. In that sense, in VOP a part of the code for structural evaluation applied in this study was specifically developed, and consisted of several simplifications, such as e.g. consideration of stiffener sizes through area, and not directly through scantlings, or application of rule-based design.



**Figure 37– Structural models used in the benchmark**

A table detailing the properties of the different codes and analyses performed in the benchmark can be found in Figure 38.

It can be noticed that the largest decrease in weight was obtained applying the modeFRONTIER optimizer linked with SAMCEF, with a 16% result using continuous variables; the actual performance is obviously somewhat lower, due to the *a posteriori* discretization of design variables. The lowest result was 3.4%, obtained with PERMAS, which however did not vary the stiffeners and frames spacing. Other methods obtained weight savings ranging from 10.8% (LBR-5) down to 9.4% (MAESTRO). Indeed, it is significant to mention that the analyses performed with very different methodologies achieved very similar results, with most results close to 10%.

The optimization performed by modeFRONTIER based on genetic algorithms, which allow a wide search within the optimization domain, led to a low thickness of the bottom plates. Yet complying with the specifications of the study, it raised the problem of Rule minimal thickness, which was not explicitly imposed by the study specifications.

This underlines the fact that any simplification of the optimization problem can lead to edge solutions, which can be very sensitive to changes of conditions (as additional requirements), all the more as the implemented algorithm allows for a wide exploration of the optimization



domain. More conservative conditions (especially concerning loads) give safer and more robust solutions, and generally speaking a robust optimization study should consider every aspect of the design, and take into account all the constraints and requirements it relates to.

Software used for optimization		MAESTRO	LBR-5	modeFRONTIER and SAMCEF	PERMAS	VOP
Partner		Cetena	ANAST	SIREHNA	Principia Marine	TKK
type of software used for optimization		ship F.E.M. gradient algorithm	ship analytical method gradient algorithm	generic F.E.M. several algo. (see text)	generic F.E.M. gradient algorithm	beam theory Genetic Algorithm
variables	frame spacing	NO	YES (constant)	NO	NO	NO
	n° of stiffeners btw girders	YES	YES	NO	NO	YES
	position of stiffeners btw girders	YES - $\Delta$ stiff constant	YES - $\Delta$ stiff constant	NO	NO	YES - $\Delta$ stiff constant
	stiffeners and girders dimensions	YES	YES	YES	NO (possible)	YES
	web thickness	YES	YES	YES	NO (possible)	YES
	flange thickness	YES	linked to geometry	YES	NO (possible)	YES
	plate thickness	YES	YES	YES	YES	YES
	discrete variable variation	YES	NO	NO (possible)	NO	YES
modelling	ship subdivision in zones	YES	YES	YES	YES	YES
	used for	preliminary design	preliminary design	prel./det. design	prel./det. design	preliminary design
	main element types	"strake"	"strake"	shell - beams	shell - beams	shell
	stiffeners modelling	YES	YES	YES	YES	NO (area)
	bulb modelling	L-equivalent	L-equivalent	L-equivalent	YES	NO (area)
	brackets modelling	"effective span"	accounted for in weight	NO (possible)	YES	NO
analysis	load cases	static	static	static	static	static
	buckling strength	YES	safety factors	check after analysis	check after analysis	check after analysis
	design of experiments	NO	NO	YES	NO	NO
results	global stress	YES	YES	YES	YES	YES
	local stress	NO	YES	YES	YES	Rule-based
	adequacy parameters	YES	NO	NO	NO	Rule-based
performance	final result (continuous variables)	---	10.8%	16%	3.4%	---
	final result (discrete variables)	9.4%	---	---	---	10.6%

**Figure 38– Summary of the optimization results**

Hence, the study did not claim winners or losers, but certainly showed the possibility for diversity of the available tools, their respective capabilities and challenges. It is worth underlying that, from the user's perspective, such as a shipyard or a design consultancy firm, not all the tools and methods illustrated are equally accessible. MAESTRO, LBR5 and PERMAS are commercially available tools embedding an optimizer. The modeFRONTIER-SAMCEF approach utilizes commercial codes but requires expertise on two environments, while the VOP approach is the most *ad hoc* method, probably viable only for academics.

## 6. Tools for structural reliability analysis of marine structures

The behavior of ships under different damage scenarios and their reliability was studied. Finite element analysis was carried out on a tanker model to find the intact ultimate strength and reliability. Also, analysis based on Smiths method were done on bulk carriers and tankers which according to the statistical study on database of accident from 1980-2007 provided by Lloyds Register has shown involved in more number of grounding and collision accident. It could be found that with both grounding and collision the ultimate strength reduces noticeably and hence reliable and fast methods of residual strength measurements should be in place. Based, on these results a reliability analysis was also carried out which showed tankers have a relatively higher reliability index compared to bulk carriers with similar percentage damage also with collision the probability of failure in sagging is higher than in hogging for both the type of ships, while with grounding accidents the probability of failure is more in hogging than in sagging.

An analytical procedure is presented for designing stiffened panels made of composite material and subjected to longitudinal compression and lateral loadings. To validate this code, predictions obtained by it were compared with finite element calculations and published experimental results. A stiffened composite panel of ship structure is investigated to consider the uncertainties associated with basic strength variables, load variable and model uncertainties in strength predictors. The reliability estimate was performed using FORM/SORM and Monte Carlo simulation and the importance of the random variables in the prediction of reliability can be determined through the sensitivity analysis. The parametric study is performed to study the effects of statistical distribution of the important variables. Finally, recommendations are made to provide guidance on applications. It was also shown that the analytical procedure is feasible and very fast for effectively analyzing for the stiffened composite panel in the preliminary and reliability-based design stages.

Risk based design methods and their applicability as tools for assessing partial safety factors as required for code formulations have been studied. Specific applications to tankers and bulk carriers in order to assess the implications of the new Common Rules as compared with the previous ones have been analyzed. A set of representative ship types have been selected, such as container vessels, bulk carriers and tankers. For these ship types the organization and the control of loading and unloading procedures were identified. Possible strategies for re-ballasting during voyage to compensate for the consumption of fuel were investigated. On this basis a stochastic model is established that can provide the joint distribution of relevant forces in the hull (Rizzuto, 2006).

Probabilistic models have been developed for the hull girder ultimate capacity of the selected ships. It was quantified the changes in notional reliability levels that result from redesigning an existing tanker ship to comply with new IACS Common Structural Rules for Double Hull Oil Tankers. The risk-based design principles have been utilized to illustrate how the target risk level and the target reliability level can be obtained for selected ship types (Rizzuto, 2005). Reliability formulations have been developed and applied in the assessment of the safety levels of intact ships subjected to combined sea states (Teixeira, Guedes Soares, 2009) and damaged ships structures due to accidental events (Luis et al. 2009, Rizzuto et al, 2010).

Rizzuto et al (2010) have examined the various elements that an effective characterization of a design scenario for a ship in damage conditions should include, highlighting the need for a proper accounting of the relationships among such elements. In particular, the dependencies on the damage extension and position of the corresponding static and dynamic loads and of the residual structural capacity of the ship were discussed, as well as the key point of the correlation between the environmental conditions during the accident.

It has been developed POD curves and methodology for ship structures including different inspection procedures. In particular a special attention has been given to rank the inspection techniques currently applied onboard with reference to the various degradation type and to identify which factors influencing inspections performances are the most relevant for each degradation type and to quantify the effects of the factors influencing inspections performances on POD and POS or at least to propose a new adequate procedure for that (Zayed et al, 2008, Lo Nigro and Rizzo, 2008).

Corrosion wastage based on long-term measurement data have been analyzed and model and to check structural deterioration and limit state functions based on the ultimate strength accounting for different deterioration mechanisms have been performed including reliability

assessment based inspection and maintenance planning (Ok et al, 2007, Garbatov et al, 2008,).

Teixeira and Guedes Soares, (2008) have studied the ultimate strength of corroded plates with spatial distribution of corrosion also represented by random fields, which were discretized using the Expansion Optimal Linear Estimation method. This preliminary study has indicated that the strength of plates with spatial distribution of corroded thickness is usually lower than the one obtained for uniform corrosion and, therefore, it is expected that this better representation of the corrosion patterns would influence the probabilistic models of the residual strength of ship plates under in-plane compression. Using the non-uniform corrosion in plates, Teixeira and Guedes Soares, (2007) have investigated how the number of thickness measurements and their location influence the correct representation of the corrosion patterns and the correct assessment the ultimate strength of the corroded plates. They showed that taking the average of the measurements to represent the corroded plate thickness in alternative to a more correct representation of the corrosion patterns, can lead to optimistic assessment of strength of the structural elements.

An approach based on the statistical analysis of failure data leading to probabilistic models of time to failure and maintenance planning has been developed. The approach adopted the Weibull model for analyzing the failure data. Based on historical data of thickness measurements or corresponding corrosion wastage thickness of structural components in bulk carriers and the progress of corrosion, critical failure levels were defined. The analysis demonstrates how data can be used to address important issues as the inspection intervals, condition based maintenance action and structural component replacement. (Garbatov and Guedes Soares 2009).

### **6.1 Risk based maintenance of deteriorated ship structures accounting for historical data**

Planning of structural maintenance of ships have been done based on structural reliability approaches involving models that represent the time development of corrosion deterioration have been proposed as for example the one presented in (Guedes Soares and Garbatov, 1998), which was recently calibrated with full-scale data in (Garbatov et al, 2007) and it has also been recently applied to analyse the reliability of a bulk carrier hull subjected to the degrading effect of corrosion. The effect of maintenance actions was modelled as a stochastic process and different repair policies including the ones adapted by the new IACS common structural rules were analysed.

Classical theory of system maintenance describes the failure of components by probabilistic models often of the Weibull family, which represents failure rates in operational phases and in the ageing phases of the life of components. This approach has been adopted in (Garbatov and Guedes Soares, 2009a; 2009b; 2010), where it has been demonstrated how it can be applied to structural maintenance of ships that are subjected to corrosion. The approach is based on historical data of thickness measurements or corresponding corrosion thickness in ships. Based on the progress of corrosion, critical corrosion thickness levels are defined as “failure”, which is modeled by a Weibull distribution. Existing formulations obtained for systems are applied to this case, leading to results that agree with standard practice.

Several sets of corrosion data of structural components of tankers and bulk carriers were analyzed. The analysis demonstrates how this data can be used to address important issues such as inspection intervals, condition based maintenance actions and structural component replacement. An effort is made to establish practical decisions about when to perform maintenance on a structure that will reach a failed (corroded) state. Different scenarios are

analysed and optimum interval and age are proposed (Garbatov and Guedes Soares, 2009a; 2009b; 2010).

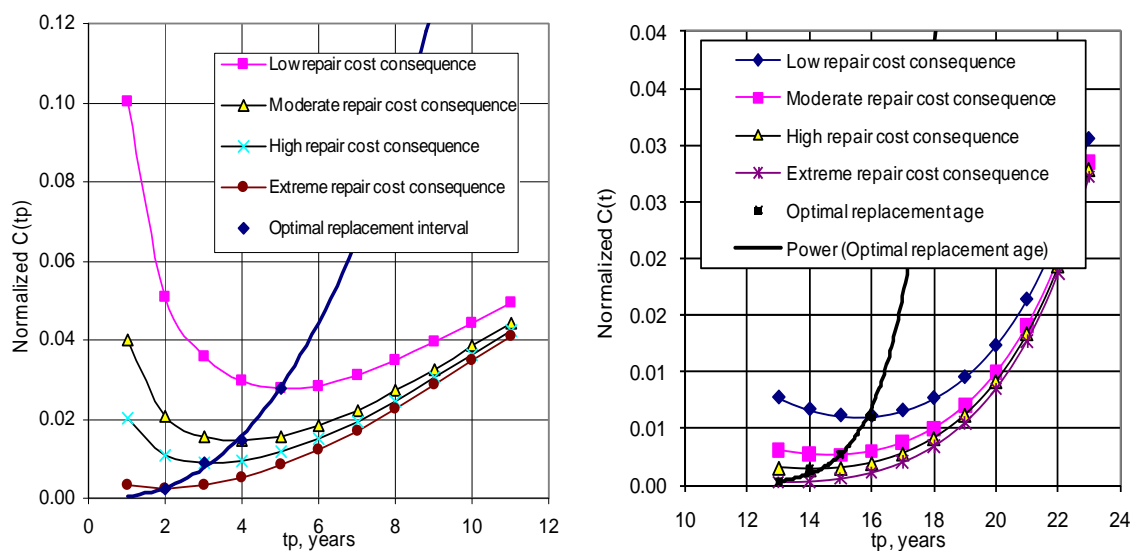
The optimum age and intervals are based on statistical analysis of thickness data using the Weibull model and some assumptions about the inspection and the time required for repair in the case of failure are considered.

Since failure is unexpected then it may be assumed that a failure replacement is more costly than an earlier replacement. To reduce the number of failures, replacements can be scheduled to occur at specified intervals. However, a balance is required between the amount spent on the replacements and their resulting benefits, that is, reduced failure replacements.

It is assumed the problem is dealing with a long period over which the structure is to be in good condition and the intervals between the replacements are short. When this is the case, it is necessary to consider only one cycle of operation and to develop a model for one cycle. If the interval between the replacements is long, it would be necessary to use a discounting approach, and the series of cycles would have to be included in the model to consider the time value of money.

No-account was taken for the time required to perform replacements since they were considered to be short, compared to the mean time between replacements. When necessary, the replacement durations can be incorporated into the replacement model, as is required when the goal is the minimization of total downtime or, equivalently, the maximization of component availability. However, any cost that is incurred because of the replacement stoppages need to be included as part of the total cost before failure or in the total cost of a failure replacement.

Optimal replacement intervals for the set of corrosion data of deck plates of ballast tanks are given in Figure left. It can be seen the minimum inspection interval is achieved when there is a combination of low corrosion tolerance and extreme total repair cost consequence, which leads to 2 years optimal replacement interval for ballast tank plates. Different variations of corrosion tolerance and total repair cost consequence result in different optimal replacements intervals (see Figure 39, left).



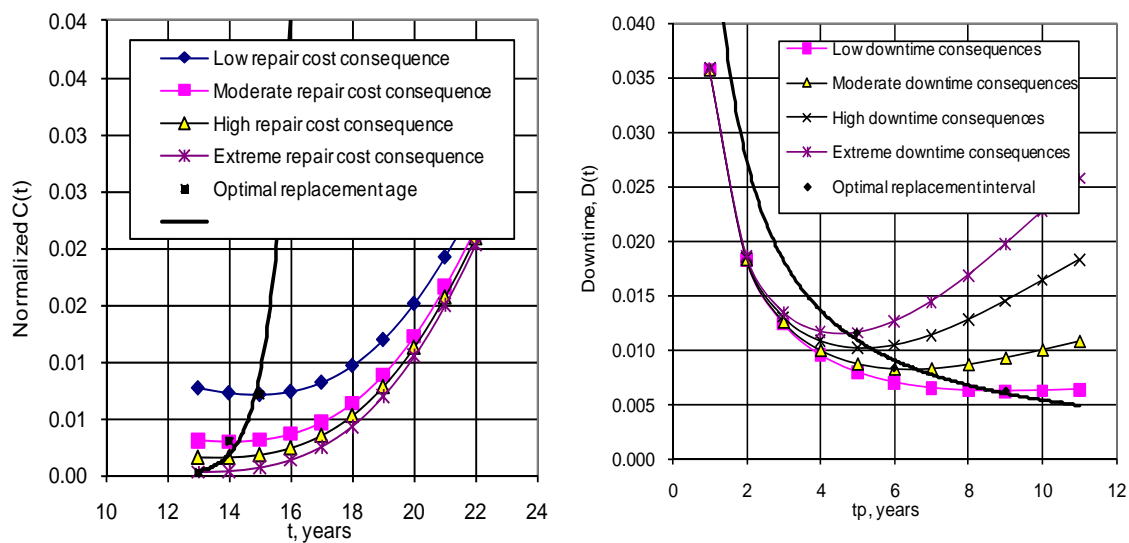
**Figure 39– Replacement intervals (left) and age (right), deck plates in ballast tanks, moderate corrosion tolerance (Garbatov and Guedes Soares, 2009b)**

The problem of optimal replacement age is similar to the one of replacement intervals except that instead of making replacements at fixed intervals, with the possibility of performing a replacement shortly after a failure replacement, the time at which the replacement occurs depends on the age of the component. When failures occur, failure replacements are made. When this occurs, the time clock is reset to zero, and the replacement occurs only when the component has been in use for the specified period.

The problem is to balance the cost of the replacements against their benefits, and this is done by determining the optimal replacement age for the component to minimize the total expected cost of replacement per unit time.

The optimal replacement age of the deck plates in ballast tanks for various repair consequences, normalized with respect to the expected cost for failure replacement for ballast and cargo tanks are given in Figure 39(right), from which it can be seen the optimal replacement ages for different combinations of corrosion tolerances and total repair consequences.

The optimal replacement age accounting for the times required for replacements for the data sets of corroded plates of the structural components subjected to corrosion is shown in Figure 40 (left) for deck plates in ballast tanks conditional to moderate corrosion tolerance.



**Figure 40 – Replacement ages (left), interval (right), deck plates in ballast tanks, moderate corrosion tolerance (Garbatov and Guedes Soares, 2009b)**

Due to difficulties in costing or the desire to get maximum utilization of structures, the replacement policy required may be one that minimizes total downtime per unit time or, equivalently, maximizes availability. The problem is to determine the best times at which replacements should occur to minimize total downtime per unit time. The basic conflicts are that as the replacement frequency increases, there is an increase in downtime because of these replacements, but a consequence of this is a reduction of downtime because of failure replacements, and we wish to get the best balance between them has been defined. The optimal replacement interval for different corrosion tolerances and downtime consequences result in different optimal replacement intervals for deck plates in ballast tanks conditional to moderate corrosion tolerance are given in Figure 40 (right), where the solid line shows the optimum replacement interval.

## 6.2 Structural safety of damaged ships

In the last two decades there has been an increasing interest in using structural reliability methods to assess the safety of ship structures. Most of the applications are related to the assessment of the implicit safety levels of ship structures for different failure modes with the state-of-the-art models and representative uncertainty measures of the strength and load variables (e.g. Guedes Soares et al., (1996), Paik and Frieze, (2001), Bitner-Gregersen et al.,

(2002)), and to calibrate design formats where a consistent reliability level is required (e.g. Spencer et al., (2003), Teixeira and Guedes Soares, (2005), Hørte et al., (2007)).

An important application is on the assessment of the notional probability of structural failure that result from different ship types as well as from different actual concepts of the same ship (Guedes Soares and Teixeira, (2000)). Also, the time dependent degrading effect of fatigue cracking and corrosion on the ultimate moment has also been taken into account in the reliability assessment of different ship types including FPSO structures (e.g. Guedes Soares and Garbatov, (1996a), Garbatov et al., (2004)).

More recently, similar reliability formulations of the ones used for intact ships have been adopted to assess the safety levels of damaged ships structures due to accidental events, as reviewed by Teixeira and Guedes Soares, (2010).

In order to be able to determine structural reliability of a damaged ship it is necessary to evaluate the longitudinal strength of the damaged hull girder and to define probabilistic models that can characterize the variability expected from the structural strength estimates.

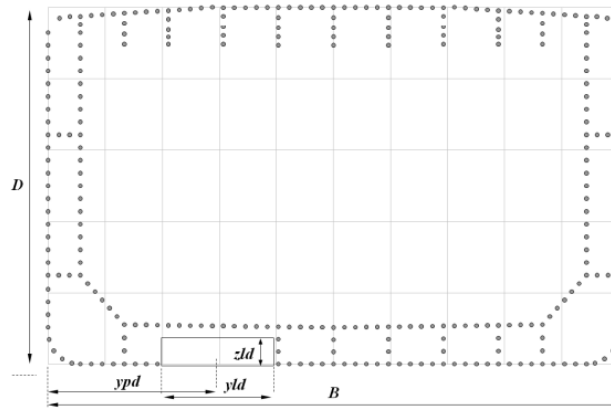
Guedes Soares et al., (2008), reported the results of a benchmark study in which the strength of a damaged ship hull was calculated with 3D nonlinear finite elements and was compared with the strength predicted by various codes based on the Smith method showing in general a good correlation. This simplified approach based on the Smith method has been used in several studies of reliability assessment of damaged ships (e.g Fang and Das (2005), Luís et al., (2009), Hussein and Guedes Soares, (2009) and Rizzuto et al., (2010)).

Fang and Das (2005) have studied the risk level of a ship damaged in different grounding and collision scenarios in different service conditions. They found that the failure probability of the ship damaged due to grounding is far less than due to collision. Moreover it was shown that the ship damaged by grounding or collision is at high risk unless necessary operational precautions are taken in order to reduce the expected loads to which the ship is subjected.

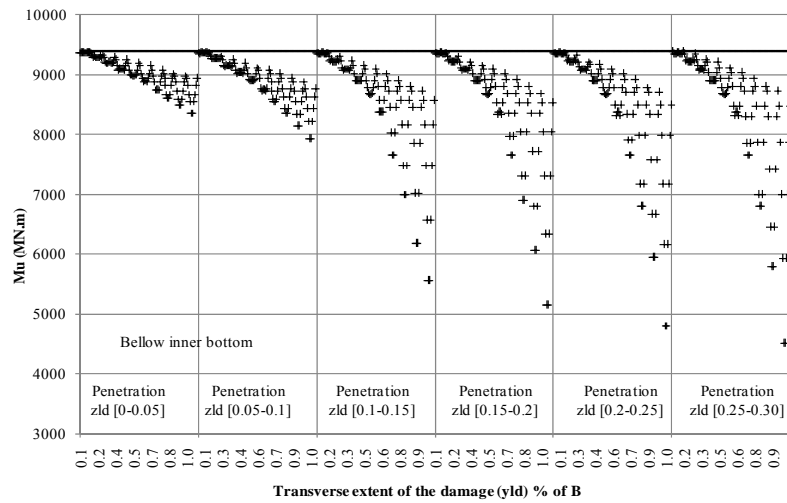
Hussein and Guedes Soares, (2009) have studied the residual strength and the safety levels of three double hull tankers designed according to the new Common Structural Rules (CSR) of the International Association of Classification Societies (IACS). Different damage scenarios at side and bottom were considered and the residual strength of the ship in each scenario was calculated. The reliability of the damaged ships was then calculated considering the changes in the still water bending moment and the decrease in the ultimate strength due to the damage. Luís et al., (2009) performed a reliability analysis of a Suezmax double hull tanker accidentally grounded. The loading of the ship was defined based on the extremes that the ship could find during one voyage of one week to dry-dock through European coastal areas. It was shown that in spite of the reliability being lower in the intact condition for sagging, in the damaged condition it is possible to find lower values for hogging, depending on the location and size of the damaged areas.

In particular, Luís et al., (2009) have assessed the effect of damages around the keel area due to an accidental grounding of a Suezmax tanker, while Rizzuto et al., (2010) have considered damage extents and locations covering all possible grounding scenarios that can occur described by a damage box as function of the transverse location ( $ypd$ ), transverse extent ( $yld$ ) and vertical extent ( $zld$ ) of the damage, as illustrated in Figure 41. Moreover, Rizzuto et al., (2010) have adopted the IMO (2003) Resolution MEPC 110(49) for the probabilistic characterization of the grounding damage.

Figure 42 illustrates the ultimate strength of the ship under sagging bending moment for the different damage cases calculated by the simplified progressive collapse method developed by Gordo et al., (1996), considering the net thickness approach ( $t=t_{net}+0.5t_c$ ) applied to all structural members according to IACS Common Structural Rules (CSR) (Rizzuto et al., (2010)).



**Figure 41 – Location and extent of damage due to grounding (Rizzuto et al., (2010))**



**Figure 42 – Ultimate strength  $M_u$  of the hull girder for the different grounding damage cases Rizzuto et al., (2010)**

In the case of damaged ships the applicable environmental conditions used for assessing wave induced loads are typically taken to be less severe than the North Atlantic model, since groundings and collisions are likely to occur in coastal areas where the traffic density is higher, as done by Luís et al., (2009). Furthermore, a reduced exposure time to the environmental conditions after damaged and before the ship is taken to a safe location should be considered when establishing the stochastic model of the extreme wave induced bending moment. Luís et al., (2009) have considered a time period  $T$  of one week as the voyage duration of the damaged ship to dry-dock and Rizzuto et al., (2010)) have used an exposure time of 24h. Luís et al., (2009) showed that the mean value of the distribution of the extreme values of the vertical wave induced bending moment can reduce in around 15% for a Suezmax tanker when reducing exposure time from one year in the North Atlantic (ATLN) to one week under the environmental conditions of European coastal areas (ECA) (Global Wave statistics (GWS) areas 27, 28 and 30, Hogben et al., (1986)).

The reliability indices of the Suezmax tanker under the two operational conditions, ATLN and ECA, obtained by Luís et al., (2009) are presented in Table 5 as a function of increasing damages around the keel area. The ECA condition also considered an increase of 50% of the still water bending moment as a result of the damage. However more accurate predictions of the still-water loads that result from the hull rupture and subsequent flooding of ship compartments can be calculated using the approach suggested by Santos and Guedes Soares, (2007). It can be seen that in general the reliability in sagging is smaller than in hogging and the reduced wave induced bending moment compensates in most of the cases the reduction in

the strength of the ship and the increased still water loads due to the damage. However, since grounding damages affect considerably the strength of the ship under hogging bending moments, the hogging reliability of the ship with large damages around the keel area may be lower than the one of the intact ship in sagging under the ATLN conditions. This suggests that the hogging failure of the ship in ballast and partial loading conditions should be analyzed carefully when assessing the structural safety of ships with grounding damages.

**Table 5- Reliability indices of a Suezmax in sagging and hogging**

	Sagging			Hogging		
	$M_{u,int} / M_{u,dam}$	ATLN	ECA	$M_{u,int} / M_{u,dam}$	ATLN	ECA
Intact	1.0	1.77	2.15	1	2.12	2.15
Damage (GCD) - 20%	0.985	1.67	1.88	0.957	1.84	1.88
Damage (GCD)	0.982	1.65	1.82	0.948	1.78	1.82
Damage (GCD) + 20%	0.979	1.63	1.74	0.935	1.69	1.74
Major Damage (GCMD) - 20%	0.983	1.66	1.67	0.925	1.61	1.67
Major Damage (GCMD)	0.979	1.63	1.52	0.903	1.46	1.52
Major Damage (GCMD)+ 20%	0.970	1.57	1.36	0.88	1.28	1.36

In the damaged condition the annual probability of failure ( $P_{f\,damage}$ ) can be defined as the product of the probability of occurrence of a damage scenario  $i$  ( $P_{damage\,i}$ ) times the conditional probability of failure given this scenario ( $P_{f\,|damage\,i}$ ), and accumulated over the number of relevant scenarios.

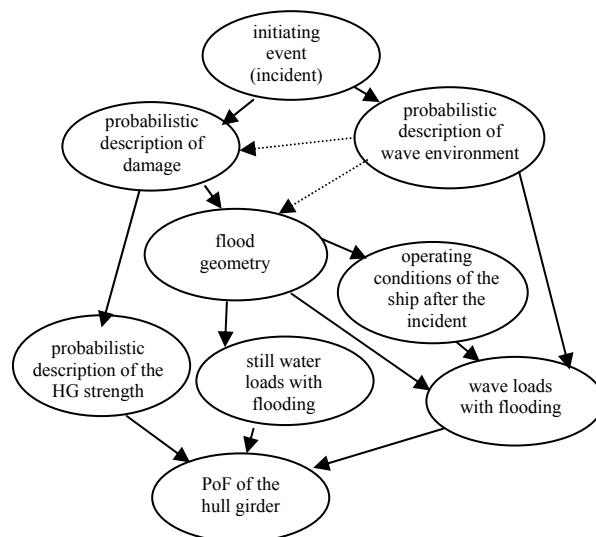
$$P_{f\,damage} = \sum_{i=1}^{all\,scenarios} P_{f\,damage\,i} = \sum_{i=1}^{all\,scenarios} P_{damage\,i} \cdot P_{f\,|damage\,i} \quad (1)$$

In practice a very limited number of scenarios need to be considered since for most of them  $P_{damage\,i}$  or  $P_{f\,|damage\,i}$  are not relevant.

The variety of damage states, depending on type, location and extension of the damage enlarges considerably the space of possible accidental conditions that in principle need to be considered in the design. A natural evolution in the definition of the damage state is the adoption of probabilistic models that can weigh the various scenarios according to their probability of occurrence.

The various elements that an effective characterization of a design scenario for a ship in damage conditions should include have been discussed by Rizzuto et al., (2010)) using a Bayesian Network model, highlighting the need for a proper accounting of the relationships among such elements. A flooding scenario is characterized in general by static and dynamic global loads, as well as by a reduced capacity. In actual terms, the extension and position of the damage in the hull envelope at the basis of the accident determines the extension of the flooding itself, the static equilibrium position, the sea-keeping performances of the hull (including wave loads) and, last but not least, the residual capacity of the hull girder. Moreover, the sea conditions may be statistically dependent (or not) on the specific accident, i.e. there could be a functional link between the sea state and the occurrence of the accident. All these aspects should be properly accounted for when defining a design scenario, which will be necessarily simple, but also realistic and coherent (in order to be representative). The possible relationships above recalled are presented in Figure 43 for the case of an incident corresponding to loss of containment in the hull envelope.





**Figure 43 - Functional diagram for an incident corresponding to loss of containment in the hull envelope (Rizzuto et al., (2010))**

Rizzuto et al., (2010) have considered a specific incident corresponding to a grounding event occurring in the hull bottom at mid-length and creating an asymmetric flooding in Ballast Tank #3 (BL3) portside. This scenario has been considered as the most relevant for the hull girder failure. However in a more general application of BN for identification of critical scenarios, the flooding of all the combinations of compartments of the ship must be analyzed. Based on this specific scenario, Rizzuto et al., (2010) have calculated the probability of failure of the hull girder conditioned to occurrence of flooding in BT3. Such a probability is shown in the second column of Table 3 for different characterizations of the sea environment.

It can be seen that the environmental characteristics influence greatly the results, because of the impact they have on the dynamic component of loads. These results in particular show the paramount importance that establishing a link between damage occurrence and the presence of severe sea states implies on the damage scenario definition.

The probabilities above reported ( $P(\text{HGF} \mid \text{F.BT3, Grounding})$ ) should be weighted in actual terms by the probability of flooding (only) BT3, conditional to a grounding event ( $2 \times 1.19\%$ ) and by the probability of having a grounding given an incident times the probability of having an incident ( $P_{25\text{years}}(\text{Ground.})$ ). The last two probabilities can be derived from tanker incidents data. These calculations are reflected in the unconditional probabilities of hull girder failure ( $P(\text{HGF})$ ) and associated reliability indices presented in the third column Table 6.

In unconditional terms, probability of failure of the hull girder in the specific damage scenario is very low, which is in line with the results of previous studies performed on the reliability assessment of damaged ships, as recently reviewed by Teixeira and Guedes Soares (2010). On the other hand, this type of probability associated to a single case has not a practical meaning. The conditional probability should instead be regarded as a value to be used in a comparative evaluation within the same class of incidents for the sake of selecting the most representative one. Once the choice has been made, the risk associated to the whole class is in principle to be transferred to the single case (design case).

Even though the specificity of the analysis developed by Rizzuto et al (2010) did not allow any firm conclusion on the selection of a design scenario for grounding events, the work

intended to give a contribution from a procedural point of view for a better treatment of accidental situations in the formulation of design checks in accidental conditions.

**Table 6-Probability of failure of the intact and damaged hull girder**

	Sea environment	P (HGF F.BT3,Grounding)	P (HGF)
Intact Ship	North Atlantic (ATLN) $T=25$ years (IACS Rec. 34)	-	$3.08E-02$ ( $\beta=1.87$ )
	South Africa (SA) (GWS Area 85), $T=24h$	$4.18E-04$ ( $\beta= 3.34$ )	$1.09E-06$ ( $\beta= 4.74$ )
Damaged Ship	SA (SD truncated) ( $H_s \geq 7.5$ m), $T=24h$	$6.50E-02$ ( $\beta= 1.51$ )	$1.69E-04$ ( $\beta= 3.58$ )
	ATLN, (IACS Rec. 34), $T=24h$	$1.38E-03$ ( $\beta= 2.99$ )	$3.61E-06$ ( $\beta= 4.49$ )
	ATLN (SD truncated) ( $H_s \geq 7.5$ m), $T=24h$	$5.36E-02$ ( $\beta=1.61$ )	$1.40E-04$ ( $\beta= 3.63$ )
	P (Flooding of BT3   Grounding) = 0.0119 (BT3 portside)		
	$P_{annual}(\text{Grounding})= 4.64E-03$ $P_{25years}(\text{Ground.})= 0.11$		

## 6. Conclusions

This paper has presented an overview of the results obtained in the MARSTRUCT project by a large number of European research groups. The summary, necessarily brief and limited has covered a set of studies that have produced interesting results, some of which unpublished yet and others briefly summarize published results. Each of the topics is aimed at being self contained in the method and conclusions obtained, although the details are not covered.

The general set of problems treated will give a flavor of what are considered relevant present day problems related with marine structures, from load assessment to strength assessment and experimentation and to design and safety evaluation. The reference list will hopefully allow the follow up of more details regarding each of the studies.

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